SUSTAINABLE TRANSPORTATION DECISION-MAKING: SPATIAL DECISION SUPPORT SYSTEMS (SDSS) AND TOTAL COST ANALYSIS

A Dissertation

by

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ABSTRACT

Building a new infrastructure facility requires a significant amount of time and expense. This is particularly true for investments in transportation for their longstanding and great degree of impact on society. The scope of time and money involved does not mean, however, we only focus on the economies of scale and may ignore other aspects of the built environment. To this extent, how can we achieve a more balanced perspective in infrastructure decision-making? In addition, what aspects should be considered when making more sustainable decisions about transportation investments? These two questions are the foundations of this study.

This dissertation shares its process in part with a previous research project – Texas Urban Triangle (TUT). Although the TUT research generated diverse variables and created possible implementations of spatial decision support system (SDSS), the methodology still demands improvement. The current method has been developed to create suitable routes but is not designed to rank or make comparisons. This is admittedly one of the biggest shortfalls in the general SDSS approach, but is also where I see as an opportunity to make alternative interpretation more comprehensive and effective. The main purpose of this dissertation is to develop a Spatial Decision Support System (SDSS) that will lead to more balanced decision-making in transportation investment and optimize the most sustainable high-speed rail (HSR) route.

The decision support system developed here explicitly elaborates the advantages and disadvantages of a transportation corridor in three particular perspectives: construction (fixed costs); operation (maintenance costs); and externalities (social and environmental costs), with a specific focus on environmental externalities. Considering more environmental features in rail routing will offset short-term economic losses and creates more sustainable environments in long-term infrastructure planning.

DEDICATION

To my families in South Korea,

To my wife, Hyekyung,

To my friends across the world,

And most importantly,

To my son, Hayden Kim, born on March 11, 2013.

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NOMENCLATURE

AHP	Analytic Hierarchy Process
ASSESS	A System for Selecting Suitable Sites
BCA	Benefit-Cost Analysis
CFA	Confirmatory Factor Analysis
DSS	Decision Support System
EFA	Explanatory Factor Analysis
EIA	Environmental Impact Analysis
EVRI	Environmental Valuation Reference Inventory
GIS	Geographic Information Systems
HSR	High-Speed Rail
MCDA	Multi-Criteria Decision Analysis
ROI	Return-on-Investment
ROW	Right-of-Way
SAS	Statistical Analysis System
SDSS	Spatial Decision Support System
SPSS	Statistical Package for the Social Sciences
TCA	Total Cost Analysis
TUT	Texas Urban Triangle

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1. INTRODUCTION AND THEORY

Planning in general refers to the process of deciding what to do and how to do something. Planning occurs at many levels, from day-to-day small-scale decisions made by individuals or families, to complex large investment decisions made by businesses and governments. Planners do not make decisions themselves; rather they support decision-makers (i.e. public officials or citizens) by coordinating information, preparing technical references, managing conflicts, and implementing activities. Their role is to create a logical, systematic decision-making process that results in the best actions. Modern society enabled and slightly forced planners to focus on conducting technical analyses or managing political influences. However, helping make good and balanced decisions remains the most creative and singular duty that planners have.

As a part of the general planning process, infrastructure planning involves an in-depth decision-making procedure for better resource and environmental management both currently and for the future. Building a new infrastructure facility requires a significant amount of time and cost. This is particularly true for investments in transportation for their longstanding and great degree of impact on society. However, it does not mean we only need to focus on the economies of scale and ignore other aspects of the built environment. For example, considering more environmental features such as endangered species or vegetation cover in railroad or highway construction may require greater cost at the beginning, but it may allow us to preserve our natural environment more ecologically and sustainably in the long run. Then, how can we achieve a more balanced perspective in infrastructure decision-making? In addition, what aspects should be considered when making more sustainable decisions about transportation investments? These two questions are the foundation of this study.

This dissertation shares its process in part with a previous research project – Texas Urban Triangle (TUT). For the past two years, the TUT team in the Department of Landscape Architecture & Urban Planning at Texas A&M University has developed a

Spatial Decision Support System (SDSS) with Geographic Information System (GIS) to draw an optimal route based on selected inputs (Kim, Wunneburger et al. 2011). These background studies have been published by the University Transportation Center for Mobility at the Texas Transportation Institute and presented in a national level conference (The Association of Collegiate Schools of Planning, 2011). Based on initial findings, the research team organized one further study focusing on developing the SDSS in a more specific way. In spring 2011, supported by a Korean engineering firm, researchers used explanatory factor analysis (EFA) to create alternative scenarios in rail route possibilities. With 17 inputs, 5 different groups were extracted using the principal component analysis with the Statistical Package for the Social Sciences (SPSS) (Kim, Wunneburger et al. 2012).

Since this project has been my main emphasis and participation for the past few years, I make progress with current research products. With the existing results, my dissertation includes a few different steps to make the proposed SDSS more sophisticated and precise. Although the TUT research generated diverse variables and created possible implementations of SDSS, the methodology demands improvement. Further, I also include ideas from transportation project evaluations so that the final route options are articulated. The current method is developed to create suitable routes, but is not designed to rank or make comparisons. This is admittedly one of the biggest shortfalls in the general SDSS approach of which I think as an opportunity to set up routines to make alternative interpretation more comprehensive and effective.

1.1 Research Purposes & Objectives

The main purpose of this dissertation is to develop a Spatial Decision Support System (SDSS) that will help make more balanced decisions in transportation investment and optimize the most sustainable high-speed rail (HSR) route. Unlike the traditional transportation impact assessment, the decision support system developed here explicitly elaborates the advantages and disadvantages of a transportation project in three particular perspectives: construction (fixed costs); operation (maintenance costs); and externalities (social & environmental costs), with a particular focus on environmental externalities. Specifically, by calculating the total costs of the proposed transportation corridor during the modeling stage, the decision support system makes it possible to fully articulate the benefits and costs associated with each investment decision. Considering more environmental features in rail routing will offset the short-term economic losses, and creates more sustainable decision-making environments in long-term infrastructure planning.

The three categories are further divided into several detailed attributes. The construction cost, for instance, thoroughly addresses the actual estimates associated with the HSR. Cost of a bridge construction or anticipated land acquisition costs are good examples. The operation field calculates travel time and the cost of maintenance. Finally, the environment category takes into account the amount of environmental resources consumed. Excellent examples are the area of wetlands destroyed or the types of vegetation eliminated. By merging ecosystem monetization with the decision-making process at the masterplan stage, each route's anticipated impacts are examined, and their implications in monetary terms become available. Specific research objectives are:

- To identify and discover a more comprehensive decision support system to rank alternatives more effectively and structurally.
- To provide more systematic solutions to weighting systems.
- To examine possibilities for the implementation of participatory GIS.
- To overcome the disadvantages in the transportation project evaluation process.
- To integrate environmental costs into the evaluation process as part of the total costs.
- To overcome the limitations in aggregate level analysis and to suggest a "bottom-up" decision-making approach in transportation investment decisions.

As can be seen, this dissertation consists of two analyses. First, the previous SDSS framework is intensively improved. Based on the existing SDSS models' inadequate implementations and limitations, improvements and modifications are more than necessary. Second transportation project evaluation is explicitly discussed.

1.2 Spatial Decision Support System: SDSS

The application of SDSS will improve to a great degree. The Decision Support System (DSS) has been a widely studied subject for more than 50 years. Since the 1950s, DSS has been actively studied and implemented in a variety of disciplines (Power 2007). With technological advances such as the invention of GIS, DSS began to be applied to problems in the spatial domain, and this new possibility became the foundations of the SDSS (Densham 1991).

However, many of the existing SDSS have obvious limitations and have been inadequately implemented in real practice. A great deal of literature works describe these limitations, which can be categorized into one of three disadvantages. First, the SDSS has limited capability in drawing alternatives. One of the main objectives for using an SDSS is that it must be possible to test alternative solutions (Uran and Janssen 2003). Because of the complexity of the SDSS, however, no distinct alternatives are generated, or countless alternatives are drawn without specific meanings. Second, not many of the systems provide support for ranking alternatives. This relates to the third limitation: most of the SDSS have little or no support for spatial evaluation, and this lack of spatial evaluation prohibits making a suitable final decision (Uran and Janssen 2003).

The other big segment of limitations with which SDSS struggles is its weighting process. A decision-making process utilizing GIS, especially raster-based GIS, requires eight steps (Wang and Hofe 2007). Of those eight steps, two require intensive inputs from the users. First, when users identify variables that are needed to achieve the overall objectives, those selected measures should be transformed into a unified scale. This is because each variable possesses different attributes inside and thus requires a transformation to a unified, numeric scale. In many SDSS cases, users are asked to replace the attributes of pixels' qualitative measures (nominal) with quantitative measures (interval, ordinal) so that the overall outcome can be interpreted in a numeric format (Basnet, Apan et al. 2001; Naidoo and Ricketts 2006). In addition, to generate the final cost surface, it is very important to differentiate each variable's implication. How researchers deal with the external weights largely drives the final outcome. To efficiently assist the weighting process, several types of decision-making approaches such as the Analytic Hierarchy Method (AHP) or the Delphi panel discussion are actively utilized.

The problem is that whether using pairwise comparison or absolute values, all rely on the consensus of an expert panel. But the availability of expert knowledge is sometimes limited and complete consensus is often difficult to achieve. Therefore, external weights tend to vary case by case and are vulnerable to the decision-making environment (Arampatzis, Kiranoudis et al. 2004). These limitations are found in the TUT project as well. The current modeling approach only deals with the AHP in its external weighting process. In other words, there is no consideration of how to effectively differentiate input variables, or under what circumstances variables need to be distinguished; the weighting process is extensively researcher-driven in nature; to overcome the limited use of variables and the overall weighting process, this dissertation incorporates the factor analysis and scenario planning techniques.

The main reason for doing a factor analysis is to identify the variables that are geographically and statistically related, and to create different groups based on the underlying characteristics of the variables. Factor analysis is a way of identifying patterns in datasets, and expressing the data in ways to highlight their similarities or differences. Of the limitations in SDSS, implementation of factor analysis and scenario planning specifically overcome the limitations in alternatives generation and the external weighting process. As long as we group the inputs based on their underlying characteristics and statistical significance, each route will indicate distinct implications. Details will be further elaborated in the methodology section. To overcome the other two limitations defined earlier, the lack of distinctive alternative generation and their spatial evaluation, improvements in the concept of transportation project evaluation is required.

1.3 Transportation Project Evaluation

Project evaluation is a set of actions used to evaluate alternatives in a transportation project (Sinha and Labi 2007). Benefit-Cost Analysis (BCA) is one of the most commonly adopted methodologies in transportation project evaluation. BCA allows testing the feasibility of a project. The prevalent pattern of a BCA explicitly addresses the demand side of a project and defines the project feasibility from a slightly biased perspective (Decorla-Souza, Everett et al. 1997). The demand side of a project, such as user forecasts, optimizes the financial feasibility. If we consider the supply (costs) side of the projects, however, the term "feasibility" becomes more complicated and diverse. The cost side of a BCA in a transportation project includes two dominant dimensions: construction costs and operation costs. Construction costs refer to the actual construction (fixed or internal) costs of a transportation project (Rocky Mountain Rail Authority 2010). Operation (maintenance) costs calculate time, safety, efficiency, fuel consumption, and so on, as alternative changes. Each alternative possesses distinct socio-economic aspects and can be valued differently.

There are, however, limitations in this approach. Experts assert that more items need to be accounted for in monetary terms, and be covered in the BCA (Decorla-Souza, Everett et al. 1997; Lee 2000; Morisugi 2000). For example, as environmental impact is considered a separate study, environmental features are often undervalued for purely conservation benefits. However, a recent practice and theory suggest that environmental features can also be counted in monetary terms. Researchers studied environmental variables such as hydrology, air pollution, and global warming, and proposed that such values should be monetarily measured in coordination with the corresponding environmental attributes (Morisugi 2000; Belhaj and Fridell 2010).

In addition, ecological economists have long studied the theoretical backgrounds as well as practical approaches to a more comprehensive monetization system of ecosystem features. They require a hybrid view of the traditional BCA, and suggest the incorporation of ecosystem monetization in infrastructure investment decisions (Bockstael, Costanza et al. 1995; Kreuter, Harris et al. 2001; Wilson, Troy et al. 2004). If we use ecosystem valuation at the beginning of the planning process, we may, at least to some extent, recapture the direct expenditures occurring from the construction or operation phases. In addition, as the characteristics of ecosystem benefits are cumulative in nature, the preserved environmental benefits become more valuable in the long run.

In reality, however, assessing the ecological aspects of a transportation project often meets obstacles. Ecology has intangible characteristics, and it is quite hard to explicitly quantify the benefits it brings to human life. In order for such elusive aspects to be identified more specifically, it is critical to review the previous research works on the ecosystem valuation. More studies on how researchers evaluated ecosystem services in monetary terms are suggested in the literature reviews and methodology sections.

To minimize the limitations in SDSS as well as to suggest a hybrid perspective on the cost side of a transportation investment decision, this dissertation adds ecosystem valuation techniques to its alternative evaluation process. Instead of just accounting for the construction and operation costs, I incorporate environmental costs as a parameter for a transportation project investment. By doing so, previously defined limitations - alternative generation and its evaluation in an SDSS – will be remedied to a larger degree, and project evaluation techniques will possess more sustainable aspects to aid investment decisions.

2. LITERATURE REVIEWS

During the preliminary exam and proposal preparation processes, around 120 articles were reviewed. They all related to the dissertation subject to a certain degree, and can be categorized into three segments. First is the literature about SDSS and decision-making in general and of relevant methods such as GIS. The studies in the second segment are about transportation project evaluations including HSR and externalities. The final segment is about the literature in ecosystem science, especially about ecosystem valuations.

2.1 Literature in Decision-Making, SDSS & GIS Modeling

The quest for a more balanced, sustainable, and rational decision-making system has lasted long enough to establish DSS as its own academic field. As briefly mentioned earlier, technological advances such as GIS made DSS not only applicable to the normal decision-making agendas, but also suitable to the problems under spatial domain (Densham 1991). This new opportunity became the foundations of SDSS, now long utilized in various disciplines. Accordingly, advantages and disadvantages have been articulated by many users. In this section, I review the recent movements in DSS literature and discover the necessary margins for more improvements. Since SDSS is a decision helping system in nature, the current issues in urban planning will first be reviewed. After that, literature works articulating the implementations of SDSS will be analyzed. Finally, an overlap between SDSS and GIS will be elaborated. SDSS utilizes spatial datasets and thus, GIS is one of the widely adopted applications.

Many scholars describe the need for more balanced and diversified inputs in the decision-making procedure. Utilizing the "bottom-up" approach, literature works require structural change in our institutional, decision-making environments. As Downs described in his 1989 paper, the citizens of the United States have long believed in the social norms that created massive spatial expansions and irresponsible use of resources (Downs 1989). According to Downs, we will need a restructuring process that preserves local authority, but still meets larger, area-wide requirements (Downs 1989). Downs' point is that the restructuring process should be primarily driven by active public participation which will eventually create more diversified inputs and considerations in the decision-making process. Such locally-oriented decisions should also coordinate well with the overall goals derived from the state or federal institutions.

Brueckner also described the need to restructure the decision-making process. In his 2000 paper, Brueckner describes main reasons as well as remedies for the U.S.'s massive suburbanization. Of those, one particular notion stands out. U.S. citizen have long been exercising their voting power to maintain a homogeneous living environments with high-income households tending to live in homogenous living environments in terms of race, income, and education (Brueckner 2000). Such desires led residents to form their own jurisdictions for the provision of public goods and services (Brueckner 2000). Exercises of biased voting power create unbalanced investments in infrastructure services, which in turn burdens entire decisions in public service provisions. According to Brueckner, such biased behavior cannot be categorized as a market failure and thus cannot be relieved with market-driven approaches. A change in the underlying structure of jurisdiction and the decision-making environment is required. How can we effectively restructure our institutional environment, especially to promote more balanced decisions? To answer this, I review Judith Innes' 1996 paper, *Planning through Consensus Building*.

Innes' article on consensus building takes on Alan Altshuler's challenges to the legitimacy of comprehensive planning and planners' expertise at large. In order to make the arguments more compelling, Innes implemented a case study approach to answer the eight critiques that Altshuler generated. As the critiques are not the main issue of this review, I will focus on how Innes interpreted restructuring via a consensus building process. According to her case studies, planning through consensus building achieved coordination with a horizontal and self-managing process rather than a top-down exercise (Innes 1996). All of her cases involved shared power across agencies and levels of government, and in between private interests and the public sector.

Therefore, a decision-making structure through consensus building requires deliberative inputs from all participants including local, state, private, and public. Innes also described in her case study how many participants began wanting to require that their local plans be checked for consistency with state policy (Innes 1996). This is possible as participants are aware of their shared, collective interests in economic, fiscal, transportation, or ecological systems. To achieve more satisfactory results among participants, it is necessary for their local plans be consistent with the bigger picture at the state or even federal levels. In this extent, a decision-making process involving consensus building can indeed be considered as a bottom-up approach, rather than a top-down hierarchy.

Institutional restructuring toward a more advanced decision-making environment can succinctly be summarized by the previous three articles. As mentioned earlier, there is a common ground that the three articles share. Brueckner describes the failures that distorted urban growth. Among many reasons, residents' voting power to achieve a more homogeneous living environment catalyzed spatial distortions. Downs explains the similar notion by criticizing the traditional norms that Americans have long pursued as an ideal. He insists that the new structure preserves local authority, but within a framework that meets area-wide needs.

Finally, Innes showed a comprehensive insight about how to achieve such a restructuring process. By implementing consensus building and participation techniques, she argues that we can preserve the local authority's authenticity in the decision-making process, and still satisfy the state's overall vision or requirements, as all the participants will be aware of their shared, collective interests on economic, fiscal, transportation, and ecological policy (Innes 1996).

If such a restructured decision-making process is utilized, especially for transportation investments like a high-speed rail, then more balanced perspectives to the overall problem will emerge. As mentioned, transportation investments are long lasting. Thus, achieving more rationale in investment judgment using a "bottom-up" decision-making process will promote the overall stability as well as sustainability. This dissertation does not explicitly deal with the restructuring process itself. However, it will intensively analyze the possibilities for more diversified inputs in transportation decisions. Utilization of SDSS in transportation investment will bring higher chance to achieve overall sustainability as it will open more opportunities to use inputs derived from both experts and related stakeholders. The first step, input variable selection in the overall research flows, is designed to achieve this objective. Then, how is SDSS actually implemented to accomplish a more balanced, sustainable decision-making environment? To answer this question, I review articles in SDSS research works and find out the shortfalls in the use of SDSS.

DSS in general refers to all types of decision helping systems, and its first use can be traced back as early as 1955 when through the Semiautomatic Ground Environment (SAGE) project at M.I.T., the idea of DSS was first proposed to the public. DSS is an applied discipline that uses knowledge and especially theory from other disciplines. Until now numerous efforts have been made to improve DSS yielding what is now six different types of DSSs (Power 2007). DSS can largely be divided into 1) communication-driven; 2) data-driven; 3) document-driven; 4) knowledge-driven; 5) model-driven; and 6) web-based systems. Among those, SDSS can be included in model-driven category (Power 2007) as its overall process to produce the final decision is closer to a model, rather than communication or a document.

In 1991, Densham gave a general overview and explained the use of SDSS. According to Densham, SDSS provide a framework for integrating database management systems with analytical models, graphical display and tabular reporting capabilities, and the expert knowledge of decision makers (Densham 1991). SDSS are explicitly designed to provide the user with a decision-making environment that enables the analysis of geographical information to be carried out in a flexible manner. The core of the SDSS is the database management system (DBMS). The DBMS must be able to store and manipulate locational, topological and thematic data types to support cartographic display, spatial query and analytical modeling (Densham 1991; Malczewski 2006; Power 2007). The characteristics of an SDSS allow it to facilitate a research process that is iterative, integrative and participative. It is iterative because a set of alternative solutions is generated which the decision maker evaluates, and participation occurs because the decision maker plays an active role in defining the problem, carrying out the analyses and evaluating the outcomes (Densham 1991).

The only shortfall at the time he was writing this chapter was the limited use of GIS. Densham specifically articulates that GIS designs are not flexible enough to accommodate variations in either the context or the process of spatial decision-making. Hence, SDSS will need to provide additional capabilities and functions that: provide mechanisms for the input of spatial data; allow representation of the complex spatial relations and structures that are common in spatial data, include analytical techniques that are unique to both spatial and geographical analysis (including statistics), and provide output in a variety of spatial forms including maps and other, more specialized, types (Densham 1991). Although GIS has been significantly developed since then, some of these constraints still remain intact and require further study. Therefore, I will review more recent articles that reduce the shortcomings identified by Densham in 1991 and attempt to uncover remaining limitations.

Three researchers tested the effects on decision-maker performance of using GIS as an SDSS in 1995. Using the analysis of variance (ANOVA) and inferential statistics such as the student’s t-test, they concluded that SDSS users experienced shorter solution times and fewer errors for different levels of task complexity. There was a significant interaction of SDSS availability and problem complexity (Crossland, Wynne et al. 1995). Even though not all of their hypotheses were proven to be statistically significant, this study has shown that an SDSS makes positive contributions to decision-maker performance, as evidenced by lower solution times and greater accuracy (Crossland, Wynne et al. 1995).

This study is quite unique as it deals with the efficacy of SDSS whereas not many other studies do. In other words, this research analyzed the effectiveness of various SDSS environment. One other notable takeaway of this study is that it suggests the needs for more studies on the usefulness of GIS as an SDSS. The authors noted that there has been a lack of basic research about the contributions of GIS to improved decision-making (Crossland, Wynne et al. 1995). Previous studies define DSS as a computer-delivered decision aid system that contains data bases, model bases, and interfaces and software that allow decision-makers or their assistants to use and alter the data and model bases in real time (Sprague 1980). GIS includes all these attributes, and thus its use as an SDSS should be dealt with more explicitly. This is one of the main reasons that I review literature in SDSS as well as GIS modeling at the same time. The effectiveness of SDSS and its use in real research is further analyzed in Uran and Janssen's 2003 paper.

In 2003, Uran and Janssen conducted a study about SDSS to answer the question of - why SDSS are not used so much, despite their well-known versatility. Using five representative examples of the Netherlands, the study searches for reasons that can explain the success or failure of SDSS (Uran and Janssen 2003). This study may be isolated to particular circumstances in the Netherlands, but their findings are meaningful to a certain degree. The first reason they identify is that users find the system too detailed, time consuming and costly to use (Ubbels and Verhallen 1999). In other words, the general complexity of the SDSS limits the involvement of users. This limitation is somewhat related to the shortfall discovered when articulating the needs for restructuring the decision-making environment. If SDSS can truly iterate and implement various users' inputs from the beginning, the overall outcome will become more balanced and participatory.

The second limitation this literature articulates is that the model output is not always suitable for direct use in decision-making. To make output useful for evaluation, comparison and ranking of alternatives and comprehensive evaluation methods are needed (Uran and Janssen 2003). Most cases described in this study provide a certain types of output result. The problem is whether the case deals with environmental issues or transportation decisions, output presentation methods are virtually identical, making it difficult for users to precisely interpret and implement the result for their needs. If SDSS is just a system to generate various alternatives without proper judgmental foundations, its use will be certainly limited. The authors discovered this limitation by reviewing the previous cases (Uran and Janssen 2003). One of the main reasons to use an SDSS is its capacity to test alternative solutions, but if no proper method is provided to test the goodness of the alternatives, the use of SDSS can largely become meaningless.

Such limitations in the overall design of SDSS can be found in other literature as well. In 2001, Janssen wrote an article about MCDA and the Environmental Impact Assessment (EIA) in the Netherlands. According to his article, opponents to the use of MCDA state that the method is prone to manipulation, is very technocratic, and provides a false sense of accuracy. On the other hand, proponents claim that MCDA provides a systematic, transparent approach that increases objectivity and generates reproducible results (Janssen 2001). He asserts that the role of MCDA is to make the decision process more transparent and the information more manageable for all stakeholders. The main methodological challenge, however, is not in the development of more sophisticated MCDA methods. More important is the support of process definition and design. Developing a new method that is supportive to generate new alternatives and is also capable of evaluate alternatives makes a major contribution to the decision-making process (Janssen 2001).

Then, what types of remedies are needed to make the overall process of SDSS more effective? In 2006, Malczewski wrote a comprehensive review of the latest materials in GIS-based MCDA analysis. His paper surveys the GIS-based MCDA (GIS-MCDA) approaches using a literature review and classification of articles from 1990 to 2004 (Malczewski 2006). According to Malczewski, GIS-MCDA can be thought of as a process that transforms and combines geographical data and value judgments to obtain information for decision-making. There are two main reasons for the rapid increase in GIS-MCDA research, the first reason being a wide recognition of decision analysis as an essential element in GIS science. The second reason can be argued to be its lower cost and greater ease of use in operation systems (Malczewski 2006). Despite such reasons, this study suggests that GIS-MCDA still has a margin to be developed in its use and implementations.

The major advantage of incorporating MCDA techniques into GIS-based procedures is that the decision-makers can insert value judgments (their preferences with respect to evaluation criteria and/or alternatives) into GIS-based decision-making procedures, and receive feedback on their implications for policy evaluation. In addition, the development of GIS-MCDA has been paralleled by the evolution of geographic information technology (Malczewski 2006). However, some articles describe that such value judgments are one of the problems in MCDA as the methods used require stakeholders or the decision makers to subjectively place importance on each of the criteria (Graymore, Wallis et al. 2009). To overcome such drawbacks, researchers argue that a sensitivity analysis is important. Malczewski in his 1999 paper argues that an investigation into the sensitivity of the alternatives to small changes (around 10%) should be carried out (Malczewski 1999).

However, as Malczewski also wrote in his 2006 paper, such value judgment interface and the development in GIS technology have also evolved GIS-MCDA from a ‘close’ expert-oriented to an ‘open’ user-oriented technology. A movement in the GIS community is underway now to use the technology to democratize the decision-making process via public participation (Malczewski 2006). In other words, similar to the previous literature, GIS-based decision-making procedures have significant possibility to incorporate public participations into its overall decision-making environment.

There are other articles indicating the need for a different type of improvement in the current SDSS particularly in relation to GIS. In 1992, Bright wrote an article about land use planning using GIS and the Statistical Analysis System (SAS) program. The suggested model, which is written in SAS programming language, begins with the use of GIS database to conduct a land suitability analysis of the study area. The second part of the model combines the results of the suitability analysis with forecasted demand for various land use types to produce optimal future land use patterns, sites for major facilities, and so on (Bright 1992).

This article provides a comprehensive review and identifies gaps in the GIS implemented suitability analyses, which is a part of SDSS. Two distinctive notions could be found in the article. First, Bright explains about the importance of the weighting system. Using logically consistent, mathematically valid methods of both assigning and combining weights is absolutely critical if the land suitability analysis process is to succeed. If great care is not taken in establishing a logically consistent weighting system that accurately reflects community goals and expert technical judgment, then the results of any land suitability model can quickly be rendered useless. Simply mapping areas that appear best for one use does not mean that an optimal land use pattern will result if any of these pixels are selected for that use; inclusion of demand and a comparison among the weights for future land use categories are needed (Bright 1992).

This is a very crucial point as most of the studies about suitability analyses still utilize inaccurate weighting systems. Such absence of a logical weighting system is the starting point for incorporating Factor Analysis in this dissertation. To minimize the sole dependency on experts' opinions and to increase logical consistency, I propose both the EFA and CFA to draw the route options in a more statistically stable manner. By doing so, grouping will be done in a more scientific fashion and the weighting system for each group will become consistent and systematic.

The second notion in this article deals with the project evaluation process that I am trying to incorporate. According to Bright, determining the best use for land is a complex process because numerous factors must be taken into consideration (Bright 1992). In the marketplace, this determination is largely based on economic factors such as the price of the land, the potential return on investment, and the development cast. Unfortunately, the marketplace does not reflect the complete costs and benefits of development. One arena where the market cost is clearly inadequate is that of environmental impacts (Bright 1992). With "optimal" defined as being public cost-minimizing and benefit-maximizing land use patterns, with environmental costs and benefits included, it requires governmental interference or a new way of estimating in the private marketplace (McHarg 1992).

This second limitation necessitates a more balanced method in the outcome interpretation, especially for more sustainable cost calculation approach. As the article was written in 1992, we have experienced technological advances, and some of the ideas to include environmental costs in the cost-benefit analysis (BCA) are achievable. Borrowing ideas such as, the Value Transfer method from ecosystem science, it is possible to estimate the amount of environmental resources consumed by a particular decision.

To overcome the limitations discovered in the previous studies, the dissertation includes a few more steps that will promote diverse inputs and will articulate the outputs in a more systematic way. By incorporating the EFA and CFA and including environmental costs in the total cost comparison, previously exposed disadvantages will be relieved to a greater degree. Merging those two steps will also remediate the limitations identified by Bright.

For the final step in this review section, it would be appropriate to analyze the literature works in the Multicriteria Decision Analysis (MCDA) as MCDA shares its foundation in part with SDSS. MCDA is considered a different type of decision-making procedure. However, its overall implications and theoretical foundations are quite similar to SDSS. Especially, when both SDSS and MCDA implement GIS, meaning that both deal with spatial problems, their problem processes become virtually identical. Therefore, I review the latest articles in MCDA research and relate it to SDSS and GIS. Numerous articles adopting MCDA or the Analytic Hierarchy Process (AHP) with GIS-modeling have been published in the past few years. From the large pool of literature, I have selected the most recent works to review, making this paper and the technology covered as timely as possible.

Many projects requiring environmental decisions actively implement MCDA for more balanced results. The common purpose of MCDA methods is to evaluate and to choose among alternatives based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision-making. The goal of decision makers in this process is to maximize utility/value, which makes MCDA a compensatory optimization approach (Kiker, Bridges et al. 2005). In 2001, three scholars conducted a suitability study to locate a new animal waste facility in Australia using a raster-based GIS with MCDA. Most of the processes are quite similar to the ones in this type of research works.

There are, however, two very notable takeaways from their research. When raster-based GIS modeling is used to do a suitability analysis, users need to conduct two particular steps, one of which is classifying the inputs into one unified scale. There have been many debates about this classification process, and the authors extensively reported the disadvantages of such a process, while also suggesting possible remedies. According to the article, Jenk's natural break and other similar classification methods (e.g., equal area and equal interval) categorize data into various suitability classes (e.g., low, medium, and high) by looking at the pattern of individual data sets. However, this type of classification does not enable the direct comparison of results because of the likelihood of varying patterns in individual data sets. Reporting the central tendency as the weighted average, weighted standard deviation, and coefficient of variation may provide a more appropriate measure if the degree of suitability of many data sets (outputs) is to be compared (Basnet, Apan et al. 2001).

The article also deals with limitations in the factor weighting process, an area where many of the previous articles found limitations. The authors describe that one major difficulty of factor weighting is the weight distribution between factors. Weight distribution is unavoidable because factors contribute differently to the degree of site suitability. However, determining the weights for input factors is often arbitrary and subjective. Typically, factor weights are determined through the consensus of an expert panel. The problem is that availability of expert knowledge is limited and consensus is often difficult to achieve (Basnet, Apan et al. 2001). Similar to what Bright espoused, a more logically consistent and systematic way to weight the inputs is necessary.

More articles can be found on the advantages and disadvantages of utilizing MCDA in the decision-making process. In 2005, three researchers developed a decision-making protocol named ASSESS (A System for Selecting Suitable Sites) utilizing MCDA, AHP, and GIS modeling. This may not be a perfect model in which all above limitations are eliminated, but it is indeed an improvement on the well-known shortfalls. ASSESS was developed to deliver outputs as spatial data that define various disciplines, to use methods for translating factor layers into standardized inputs for problems, to use new methods for capturing uncertainty in ranking of alternatives, and to explore options for quantitative optimization with or without a spatial component (Hill, Braaten et al. 2005).

These characteristics are very similar to the SDSS process that the TUT research team has been developing.

The authors defined two key issues in their ASSESS system. The first concerns the introduction of new quantitative methods at a number of stages in MCDA for landscape-scale problems and how these methods can be reconciled and assist with the human decision-making process in an iterative and user-friendly way. The second concerns the utility and feasibility of incorporating spatial analysis into existing MCDA or the redesigning of MCDA as a seamless spatially explicit process (Hill, Braaten et al. 2005). In other words, they are concerned about the ways to represent qualitative datasets in more quantitative or iterative ways in the overall decision-making process. Further, their second concern deals with the modifications or improvements of the existing MCDA to make the process work better within the spatial domain.

Their solutions to the above two issues are grouping and scenario comparison, both of which my dissertation attempts to include to some extent. Their input data, whether categorical, ordinal or numerical, are converted to relative ratings from 1 to 5 representing high to low suitability or quality. These input data may be grouped by theme based on biases, paradigms, goals, prejudices and objective categorization, and create a range of scenarios (Hill, Braaten et al. 2005). The only shortfall in this grouping process is that ASSESS relies on intuitive approaches in the grouping process. No scientific or statistical methods were implemented to group the inputs when creating possible scenarios. This is quite a subjective process as their justifications are either not solid enough to persuade the users or are too general to provide a foundation to the grouping process.

After this grouping step, each scenario is compared with different viewpoints where redundancies, correlations and interrelationships between the data are revealed. This is one more shortfall as there are no quantifications of scenarios being made (Hill, Braaten et al. 2005). As the authors acknowledge, MCDA could be greatly improved by having a suite of different quantitative methods and approaches available to the user such that uncertainty could be explicitly propagated, various fuzzy and probabilistic approaches could be applied, and optimization could be chosen (Hill, Braaten et al. 2005). In other words, if a quantification method is utilized during the final comparison process, MCDA's reliability and judgmental stability will greatly improve.

Similar to what Basnet et al. and Bright discovered, two points are very critical as they all relate to the goal my dissertation is heading to. If my approach could improve the grouping process by implementing a more systematic and scientific method through Factor Analysis, and could suggest more quantifiable methods to make the final comparison analytical, it would significantly improve the current practices in MCDA research works.

So far, about 20 literature works about SDSS and GIS have been extensively reviewed. Based on the results, the limitations or gaps in the current SDSS research can largely be categorized into two aspects. First, as Uran and Jenssen described, there is a need for a more improved, systematic design in the overall SDSS procedures. Specifically, the input selection and its use can become very subjective or too dependent. GIS-based SDSS can insert value judgments into the decision-making procedures, and how users input values largely drives the outcome (Malczewski 2006). To minimize any possible errors and increase the reliability of the result, Malczewski suggested two possible remedies. First, we can conduct a sensitivity analysis and test the sensitivity of the alternatives to small changes. In this case, less than 10% is respectively acceptable (Malczewski 1999).

The other possibility is the increased use of participatory GIS. Technological advances in GIS-MCDA have enabled users to actively implement inputs via public participation. Identifying inputs with public participation would decrease the sole dependency on experts' opinions and expand the validity of input variables. If this dissertation could include the two into the modeling process, the limitations in the overall process design will improve to a great degree.

The second gap relates to the weighting system and the resulting interpretation. As Bright argued in her paper, if we cannot create a logically consistent weighting system, the output can quickly become useless (Bright 1992). Further, as noted in the ASSESS article, the subjective nature of weighting systems can be relieved with a grouping process but we are still faced with the need for more scientific and systematic ways to group the factors. I expect utilizing Factor Analysis technique would improve the gaps in the weighting process. By using statistically significant results, the grouping process will have more solid foundations and reliable justifications.

In addition, as both Bright and the ASSESS article described, the outcome should be interpreted more quantifiably. GIS-MCDA can be improved with quantifiable comparisons (Hill, Braaten et al. 2005), but the marketplace approach cannot capture the true costs associated with the decision-making process, and we need to consider some indirect costs such as those to the environment. Therefore, having a more comprehensive quantification method during the final comparison process will improve GIS-MCDA's reliability. The Value Transfer approach suggested in this dissertation will greatly help capture the indirect environmental costs and will offer a more quantifiable method for interpreting the outcome result.

2.2 Literature in Transportation Project Evaluation, Externalities, & HSR

Transportation literature is reviewed in two parts. First, studies evaluating transportation projects will be reviewed, especially with respect to need for more diversified, comprehensive evaluation attributes. After that, literature about transportation externalities, which articulates the environmental externalities, will be covered.

As described earlier, project evaluation refers to a set of actions for assessing alternatives in a transportation project (Sinha and Labi 2007). According to Hayashi and Morisugi, there are about six components in project evaluation: 1) demand forecast; 2) value of time; 3) safety; 4) environmental impacts; 5) efficiency; and 6) economic impact. In addition, the prevalent methodology used in the evaluation process is the benefit-cost analysis (BCA) (Hayashi and Morisugi 2000). This article is very useful as the authors provide background of evaluation processes of five different countries: the United Kingdom, Japan, Germany, France, and the U.S. Despite three of the countries calculating monetary values for environmental features consumed by a transportation project, the U.S. calculates environmental resources in a separate study via a point system, not necessarily as features of financial significance (Hayashi and Morisugi 2000). As can be seen in table below, most criteria are quite similar across the five countries. The biggest difference is in efficiency as each country sets different discount rates and project durations. Further, the U.K. and U.S. are the only ones where environmental features are not calculated in monetary terms. Table 1 summarizes the results.

Other literature also supports the need for monetary values of environmental features. In 2000, Lee conducted a very similar study about the U.S.' project evaluation criteria and main methodologies. In his article, Lee argues that the evaluation process can be separated into three segments: 1) alternative generation; 2) impact estimate; and 3) evaluation and selection (Lee 2000). As the U.S. uses the abovementioned six attributes in the evaluation process and impact estimate, consideration of environmental costs are often left out. According to Lee, there are mandatory procedures for some fixed costs, such as loss of habitat, wetlands, and parks, because federal law many years ago imposed the constraint of no net loss. If another route was impossible, then whatever natural resources existed prior to construction had to be replaced in kind (Lee 2000). Nonetheless, the current practice still lacks a means to systematically measure the environmental costs consumed by a specific project.

Table 1 Project Evaluation Criteria of Five Different Countries

	UK	France	Japan	Germany	USA
Demand Forecast	4-step modeling	4-step modeling	4-step modeling	4-step modeling	4-step modeling
Value of Time	Wage rate (working type + vehicle type)	Wage rate (working type)	Wage rate (working type + vehicle type)	Wage rate (working type + vehicle type)	Wage rate (working type)
Safety	Value of life Physical damage Other costs	Material damage Physical damage Injury Fatality	Material damage Physical damage Injury Fatality Other costs	Material damage Physical damage Injury Fatality	Material damage Slight injury Severe injury Fatality
<Value of life>	$1.0 million	$0.56 million	$0.27 million	$0.79 million	$2.6 million
Efficiency	30 years 6% discount rate	20 years 8% discount rate	40 years 4% discount rate	40 years 3% discount rate	20~50 years 7% discount rate
Economic Impact	Input-Output analysis	Input-Output analysis	Input-Output analysis	Input-Output analysis	Input-Output analysis
Environmental Impact	Not evaluated in monetary terms	Evaluated	Evaluated	Evaluated	Not evaluated in monetary terms

To make up for the limitations of the evaluation process, there have been some efforts to consider environmental features as a part of externalities. Beginning in the early-2000s, researchers and scholars started focusing on environmental externalities in transportation projects (Lee 2000; Adamowicz 2003; Janic 2003; Lu and Morrell 2006; Belhaj and Fridell 2010). Most of them calculated the externalities in congestion, noise, and air pollution. Some studies include such features in BCA and estimated the monetary result. For example, in Lu and Morrell's paper, they examined different sized airports and included noise and emission costs to BCA as externalities (Lu and Morrell 2006). The result indicates that approximately 450,000 airplane movements per year create an intersection between marginal economic benefits and marginal environmental costs. In other words, if an airport creates more than 450,000 movements per year, then the associated costs are greater than the economic benefits. The only shortcoming of this approach is that environmental externalities are only limited to the three aspects and true calculation of ecosystem consumptions is not thoroughly considered.

In 1999, two researchers calculated the marginal environmental costs of transportation systems in Greece at three different scales: local, regional, and global (Vossiniotis and Assimacopoulos 1999). This article is a good example as it shows the directions for similar future studies. According to the authors, environmental costs arising from transport activities by one group of persons and imposed on another group of persons, without being fully accounted for by the first group, are considered to be external. Traditional economic analysis included fixed and operational costs and ignored externalities like this (Vossiniotis and Assimacopoulos 1999). How do we improve upon an absence of externalities? Their findings and conclusions suggest that the resulting environmental damages depend heavily on the technology used and the location of the transport activity. The application of the methodology reveals a great variation of the environmental costs of transport depending on the transport mode, the emission control technology used, and the location of the transport task (Vossiniotis and Assimacopoulos 1999). In other words, transport externalities are especially site-specific and depend heavily on the nature of the project. Therefore, should externalities be estimated on a case-by-case basis, the inclusion of context-specific measures will indeed have an impact on the final investment decision.

The needs for more location-specific externalities are found in other articles. In 2003, a handbook about transportation and environment was published. The book consisted of numerous articles under 45 different chapters with specific chapters relating to environmental externalities and transportation planning (Hensher and Button 2003). In chapter 19, Quinet wrote of techniques and approaches needed for environmental impact assessments. According to the article, location-specific measures are necessary to reply to the questions on geographic aggregations. It means that, ideally speaking, we need to measure transportation impacts on the environment with a “bottom-up” approach, cumulatively measuring the impacts from a small to larger scale. In cases where data availability is lacking, however, this can be hard to achieve. Therefore, “top-down” approaches are often used to assess the impact (Quinet 2003). The shortcoming of using aggregate-level analyses is that we cannot distinguish with any degree of precision between local situations or the types of transportation used (Quinet 2003).

One other good source to understand the externalities in transportation planning is Belhaj and Fridell’s 2010 article. This article is a literature review on external costs related to goods transport where an array of method and model as well as some of the derived external costs are presented to give insight on the levels of these costs linked to health, ecosystems and the built environment (Belhaj and Fridell 2010). According to the authors, an externality is "an effect of a purchase or use decision by one set of parties on others who did not have a choice and whose interests were not taken into account" (p2). Externalities may become positive or negative. Negative externalities arise when an action by an individual or a group implies harmful consequences for others, such as air pollution or effects on health, forest growth or fish reproduction. A positive externality may be the result of actions by an individual or a group benefiting other, with an example being technological spill-over. In the case of positive externalities, the social benefit is larger than the private benefit, while the opposite applies for negative externalities (Belhaj and Fridell 2010).

There are other types to capture externalities. Environmental Impact Analysis (EIA) is one of the prevalent forms in environmental impacts evaluation. Even though EIA in general does not require monetary estimates, environmental externalities are well captured in EIA process. In the previously mentioned handbook, a chapter by Dhingra et al. is dedicated to explaining EIA. The authors write that EIA may be defined as a formal process to predict the environmental consequences of human development activities and to plan appropriate measures to eliminate or reduce adverse effects and to augment positive effects (Dhingra, Rao et al. 2003).

They also suggest how to conduct an EIA. According to the article, EIA is calculated using a weighting standard. There are five categories to be considered: travel impacts; air quality; noise; ecological impacts; and socioeconomic impacts (Dhingra, Rao et al. 2003). Using pre-established equations and formulas, each category's impact scores are estimated. Finally, the most suitable alternative is selected, or mitigation measures are examined if there is no other way to change the project. The only problem with such a traditional EIA approach is that it is very hard to understand the exact damages in social and financial terms as it only utilizes a point system. Thus, we can only compare the degrees of damages created by a project. This is plausible if we need to consider short-term effects. but environmental impacts are cumulative and long-lasting in nature, and a short-sighted view seems not so sustainable in the long run. We need a more comprehensive evaluation method for EIA and externalities general.

What other types of methods can be used to examine the externalities in transportation planning? As previously mentioned, BCA is one of the most widely utilized methods in project evaluation process. Here, I will review the articles in transportation BCA, especially focusing on externalities.

In chapter 18 of the Handbook of Transportation and Environment, three researchers wrote of the uses and limitations of traditional BCA, particularly within the domain of the environmental costs. According to the article, there are two well-known limitations to BCA (Nijkamp, Ubbels et al. 2003). First, BCA requires second-best conclusions for more comprehensive environmental costs evaluation. Otherwise, there are no proper comparisons available and the solution becomes the only practical and possible option. Second, choosing the right discount rate and project duration are keys to the final outcome. Like the article suggests, environmental deduction should be discounted at a low or even zero rate as these impacts are long run in nature. They involve intergenerational equity and may become practically insignificant (Nijkamp, Ubbels et al. 2003). To minimize the shortcomings of BCA, several complementary approaches such as cost-effectiveness or total cost analysis are deployed in some cases. No matter what types are used, the main purpose of the public investment should be social welfare maximization, not the profit maximization usually seen in private investment decisions (Nijkamp, Ubbels et al. 2003).

In 1997, two scholars wrote about an approach that offsets the well-known limitations in BCA. According to the article, BCA has been used less by urban transportation decision-makers in the U.S. for several reasons. Many factors other than economic efficiency are important to the decision-makers but are difficult to enumerate in monetary terms and may even be non-quantifiable (Decorla-Souza, Everett et al. 1997). Further, the term "benefits" in BCA is quite subjective and requires scrutiny in defining the scope of benefits induced by a project (Decorla-Souza, Everett et al. 1997). Therefore, the authors' suggestion is to use Total Cost Analysis (TCA) because it is easily understood by the public and political decision-makers than BCA concepts such as "net present worth", "benefit-cost ratio" and "internal rate of return". A second advantage of using TCA is that there is no suggestion that all "benefits" have been considered; decision-makers are free to use their own value judgments to trade off total cost against non-monetizable social, environmental and economic impacts, just as they trade off quality and convenience against cost when purchasing goods and services in their roles as consumers (Decorla-Souza, Everett et al. 1997).

The TCA approach presented in this paper is actually quite close to a form of BCA. In the TCA approach, benefits involving "cost savings" are automatically considered on the "cost" side of the equation, instead of separately as "benefits". In BCA, most or all monetized benefits are really cost savings (Decorla-Souza, Everett et al. 1997). TCA is especially powerful when evaluating the alternatives. With the TCA approach, a common evaluation measure (i.e. total cost) is computed across all types of alternatives. The effectiveness of alternatives with respect to transportation service is measured in terms of the increment of trips. Thus, cost-effectiveness of alternatives can be measured in terms of incremental cost per additional trip accommodated (Decorla-Souza, Everett et al. 1997). If used with a proper care, TCA may reduce the limitations in BCA and provide more comprehensive results in alternative comparisons.

More criticisms of using BCA and suggestions for a supplementary method can be found in other literature. In 2000, De Jong wrote an article about the effectiveness of using MCDA in transportation evaluation over the use of BCA (De Jong 2000). According to the article, a common argument in favor of the traditional BCA is the unambiguous quantitative number it produces. Proponents of this line of evaluation blame all other non-monetary methods for creating the illusion that without weights attached to them all criteria seem of equal importance. Supporters of MCDA techniques are convinced that it is theoretically and practically impossible to reflect the desirability of transport infrastructure projects as just one number, even if methodologists try as hard as they can (De Jong 2000). In addition, some elements in BCA, especially among the ecological and safety aspects, require data which are not always available or immediately at hand. This leads to situations in which applicants are freed from the obligation to complete that part of the evaluation (De Jong 2000). This is partly true that not all the criteria are the same, nor need to be treated equally important. To this extent, using MCDA over BCA seems appropriate. However, there are also limitations of using MCDA in evaluation process.

In 2007, three Dutch scholars conducted a study about the use of BCA in transportation projects in the Netherlands. The paper reviews the Dutch standardized BCA practice since 2000 (Annema, Koopmans et al. 2007). According to the article, MCDA has the disadvantage that the basis for the weights assigned to the effects are often unclear and that there is a real danger of double-counting because clear criteria to include effects in a MCDA is nonexistent (Annema, Koopmans et al. 2007). In addition, the article also suggests criticisms of BCA, summarized into four main points. First, some scientists argue that BCA represents a flawed appraisal method. One of the basic principles of

BCA is that all impacts of a project on individuals are valued on the basis of the impact issue, for instance, asking whether it satisfies or dissatisfies individual preferences. This seems to suggest that people cannot be relied on to find their own interests and that someone else must deem certain goods and conditions important for a good life. For example, someone will have to protect nature/endangered species when building a new—economically highly attractive—port in a wildlife area (Annema, Koopmans et al. 2007).

The second criticism of BCA is that the market analogy valuation methods for non-priced goods, required in most BCAs for infrastructure projects, are inherently flawed. As the critics say, it is especially the common methods of valuing environmental impacts in BCAs that cannot possibly result in a true picture of the real values people attach to goods such as nature, landscapes or a clean environment. A third point in the debate is that some people worry that BCA will easily result in incomplete or incorrect information to the decision-makers. The final criticism is about the difficulty of valuing non-priced environmental goods. The ecological effects, for instance, have been only partly expressed in monetary terms in the BCAs, especially for emissions and noise (Annema, Koopmans et al. 2007). Despite such criticisms, the authors suggest that BCA with careful measures and considerations will surpass the limitations in the use of MCDA.

There is one particular notion in this article about BCA and ecosystem valuation. According to the authors, the information on the ecological and distributional effects of infrastructure requires improvement. As these effects are not expressed in monetary terms, they tend to receive less attention from policymakers than the financial balance (Annema, Koopmans et al. 2007). This is exacerbated if researchers stress the financial balance in their conclusions, leaving out other effects. As non-financial effects are mostly costs, not benefits, this distorts the overall picture of the project. This is very important as it lays the foundation for and justifies including ecosystem services in monetary terms in the evaluation process.

There is one more article describing the need for more comprehensive measures in the evaluation process. In 2011, three experts wrote about the use of MCDA in transport project evaluation. Their article provides a comprehensive comparison between various evaluation techniques used in the transportation planning. According to the authors, decision-makers can choose among a large number of evaluation techniques to assess transport projects, including BCA, multicriteria analysis (MCA), cost-effectiveness analysis (CEA), regional economic impact study (REIS) and environmental impact assessment (EIA) (Brucker, Macharis et al. 2011). Such approaches should be adopted based on cases and project characteristics, but the authors suggest two distinctive points that are of interest.

First, they suggest designing a traditional value structure, a criteria structure identical for all stakeholders, but whereby each stakeholder is given the possibility to enter his individual preferences through specific weights. This can be achieved through implementing a specific type of sensitivity analysis called "scenario analysis" (Brucker, Macharis et al. 2011). This is very useful as different scenarios create different results, and the results imply different consequences. In accordance with the use of scenario analysis, the authors also explain the need for including more ecosystem features in the evaluation process.

According to the article, in a perfect market, which is the standard assumption in neo-classical economics, the priorities derived via market demand would be expected to reflect those derived via market supply, and no government or public policy intervention would be required. It is thus assumed that what would be good for individual users would also be good for society. This is definitely not the case here and for several reasons. First, there are a number of external effects, such as effects on safety (including on third party users like pedestrians and cyclists) and environmental effects. Second, infrastructure being a public good can only be financed with government funds allocated by public policy makers. Third, there may be bounded rationality challenges, and consumer preferences may be inconsistent over time. When deciding on the type of goods to buy, consumers often have a preference for goods resulting in immediate but short-lived benefits and associated with large costs or sacrifices in the future.

These future costs or sacrifices are often underestimated at the time the decision is made illustrating why market intervention by public policy makers is required. Fourth, the tools or systems analyzed are highly innovative and the market for them still has to be developed. In such cases, government incentives or an active supply-side policy by government can be instrumental in stimulating and forming the institutional structures of this evolving market (Brucker, Macharis et al. 2011). These are very crucial points as all of their implications call for more balanced and clarified judgmental tools in project evaluation. This is the foundation for including ecosystem valuation in my dissertation.

So far, literature about BCA and environmental externalities has been reviewed, but how are such perspectives implemented in HSR routing? As this dissertation deals with HSR route optimization, reviewing the articles in HSR planning in relation to the aforementioned two perspectives is an important part of this process as well. HSR, though a quite recent development in the U.S., is a very controversial issue in that country's urban planning discipline. In other countries, on the other hand, HSR is a widely studied subject, especially in engineering fields. In this sense, choosing the right literature in relation to the overall subject of my dissertation is important. In this review section, I focus only on HSR articles covering environmental externalities and the costs side.

In 1999, Levinson and two other researchers studied the total costs of HSR, air, and highways to test the effectiveness of HSR operation in the state of California. This study included estimates of four types of external costs: accidents, congestion, noise, and air pollution and compared performance in each category by each mode (Levinson, Kanafani et al. 1999). The authors first specified the full costs of each mode. According to the article, the full long-term cost calculation includes the internal cost of building, operating, and maintaining infrastructure, as well as carrier, user, and external or social costs such as noise, pollution, and accidents. Despite the different natures of these technologies, it is nonetheless possible to compare four categories broadly defined as: infrastructure costs, user operating costs, carrier operating costs, and social costs (Levinson, Kanafani et al. 1999).

The final result is quite interesting as the overall costs for air are less than the others. The full cost of air is about \$0.1315 per passenger-kilometer traveled (pkt), whereas the full cost of HSR and highway are \$0.24/pkt and \$0.23/pkt, respectively (Levinson, Kanafani et al. 1999). However, if social costs are compared, HSR costs the least. HSR costs about \$0.002/pkt, which is lower than that of air at \$0.0043/pkt and highway at \$0.0045/pkt (Levinson, Kanafani et al. 1999). Since the study was conducted in 1999 when one gallon of gasoline was usually less than \$2.00, I will not discuss the validity of the study. Nonetheless, this article is interesting as it suggests appropriate guidelines for comparing different modes in terms of their total costs. As the authors defined, there are three elements of total costs: internal (fixed) costs; operating (maintenance) costs; and external (social) costs. Further, the authors categorized the fixed costs into land, rail capital, and investments; and operating costs into operating and maintenance costs. Finally, social costs are described with air pollution, noise, safety, and congestion (Levinson, Kanafani et al. 1999). These attributes and guidelines are very useful and my dissertation partly reflects such notions in the alternative evaluation process.

Similar comparisons can be found in other literature. In 2003, Janic wrote an article presenting an overview of the environmental performance of HSR and air passenger transport (APT) in the European Union (EU). Environmental performance, as used here, included the direct environmental burdens such as energy consumption, air pollution, noise, land-take and land use, safety and congestion (Janic 2003). The result shows that HSR has better environmental performance than APT, meaning that any kind of substitution, either through competition or complementarity, and driven at present mostly by the commercial viability rather than by the environmental constraints, would contribute to mitigation of the cumulative environmental damage (Janic 2003). According to the article, HSR consumes less energy and lands, creates less air pollution and noise, and increases safety.

This article provides in-depth overview of HSR and environmental externalities. The author states that both HSR and APT create direct burdens. Direct burdens include energy consumption, air pollution, noise, land-take and land use, safety and congestion. The first four have a physical dimension, and the last two have a social dimension. All have an economic dimension in the form of external costs of the perceived or real environmental damage. The level of direct burden and their short-term impacts are primarily dependent on the duration of the operations and activities causing them. However, the cumulative effect of short-term impacts is that, collectively and in the long-run, they are damaging to the environment. Energy consumption and air pollution may cause both local and global damage (Janic 2003). In addition, the author also argues that the marginal external costs are generally lower for HSR than APT, which indicates that this system has better environmental performance. However, for full-scale comparison and assessment of the effects of substitution, the operational and passenger time costs of the systems as well as the real load factors on particular corridors should also be taken into account (Janic 2003).

This is a very interesting point as it shares the limitations in the previously described literature. There are ways to determine how HSR is doing well in its environmental performances by calculating externalities, but it still demands more scrutiny by including location-specific and project basis measures. Janic explained the needs for more detailed attributes in total costs comparisons, especially for environmental costs. This limitation will significantly improve by merging ecosystem valuation techniques such as Value Transfer.

More articles on the cost assessment of HSR can be found. In 2010, two researchers conducted a study to assess the environmental costs of four modes: auto, rail, HSR, and air. The study evaluated both direct effects of vehicle operation and indirect effects from vehicle, infrastructure, and fuel components (Chester and Horvath 2010). According to the authors, HSR may lower energy consumption and greenhouse gas emissions per trip and the California High-Speed Rail (CAHSR) system offers the potential to provide lower energy and emissions transportation (Chester and Horvath 2010). This article is unique as it provides different measurements in mode comparison. The authors not only calculated the associated costs but also estimated the demand and suggested the return on investment (ROI) at three levels of possibility: high, mid, and low occupancy. According to the article, low occupancy is set at 120 passengers (10% occupancy of the longest trains, a proxy for a mostly empty train) and the high as 1200 passengers (maximum seats on the longest trains). The CAHSR Authority has completed an energy assessment using an average occupancy of 761 passengers (63% utilization) when the system is fully constructed and is operationally mature (California High-Speed Rail Authority 2005), and this study followed the same principle in calculating the medium occupancy (Chester and Horvath 2010). The result is quite compelling. If medium occupancy is used, then CAHSR will take 71 years to yield a full return on investment on its energy consumption, and it will be impossible to reach a full ROI with a rate of low occupancy. The high occupancy will reduce ROI on energy to six years (Chester and Horvath 2010).

The implications of the 30 articles reviewed can be summarized into two catagories. First, a traditionally dominant method in project evaluation, Benefit-Cost Analysis (BCA), lacks the ability to adequately reflect the true costs associated with a project. As

Morisugi and Hayashi described in their paper, the U.S. traditionally excluded the environmental costs in its exercise of project evaluation (Hayashi and Morisugi 2000). Environmental impacts are considered a separate study and conducted in an Environmental Impact Analysis (EIA). EIA is unique in its process and designed to capture the environmental changes due to man-made structures. The only shortcoming is its point system and that it lacks interpretation in socioeconomic terms (Dhingra, Rao et al. 2003). BCA also represents a flawed appraisal method as the market analogy valuation methods for non-priced goods, required in most BCAs for infrastructure projects (Annema, Koopmans et al. 2007; Chester and Horvath 2010). Therefore, there are some other complementary approaches suggested by experts such as Total Cost Analysis (TCA) or MCDA (Decorla-Souza, Everett et al. 1997; Brucker, Macharis et al. 2011). If used with a proper care, TCA may provide more comprehensive results in alternative comparisons, and this will become a very useful tactic in my dissertation.

The second notion is about the need for ecosystem monetization in the evaluation process. As noted, transport externalities are especially site-specific and depend heavily on the nature of the project (Vossiniotis and Assimacopoulos 1999). In other words, externalities should be dealt with carefully and should include more precise measures. By doing so, we will be able to achieve what Quinet described as an ideal, “bottom-up” approach in calculating the transport impact (Quinet 2003). Further, as Annema et al. noted, value of ecosystem features have been received less attention as BCA cannot fully capture the monetary terms of indirect costs (Annema, Koopmans et al. 2007). To avoid this absence, Brucker et al. suggest governmental intervention in pricing environmental services (Brucker, Macharis et al. 2011). Needs for a more context-specific approach are also found in high-speed rail research works. Like Janic suggested in his 2003 paper, for full-scale comparison and assessment of the effects of substitution, the operational and passenger time costs of the systems as well as the real load factors on particular corridors should also be taken into account (Janic 2003). In addition, Levinson created a unified framework to compare different modes of transportation (Levinson, Kanafani et al.

1999). Even though the validity of his research is questionable and the use of aggregated level analysis is not so precise, his suggested framework is quite compelling and relevant to my dissertation as well.

These are important points and have become very plausible as technology has progressed to a point where location-specific estimates are now possible. Implementation of GIS or utilization of satellite images enables researchers to pinpoint the changes in ecosystems induced by man-made structures, and this is the direction that my dissertation is aiming during the alternatives evaluation process. Exposed limitations will be improved upon as more location-specific ecosystem valuations are incorporated with Value Transfer technique and GIS. In addition, such precise measurements in total costs will bridge the gaps in the use of BCA described by many previous researchers. Using the supplementary methods such as the TCA and ecosystem valuation, well-known limitations in BCA and EIA will improve to a greater degree.

2.3 Literature in Ecosystem Valuation

Ecosystem valuation is a relatively new field in ecosystem sciences, but with the significant contributions from well-known scholars such as Robert Costanza, the value of ecosystem services are now being estimated in economic terms (Costanza and Daly 1992; Costanza, d'Arge et al. 1997; Costanza 2000). In this review section, I will first explain the general and theoretical backgrounds of the ecosystem valuation discipline and then will review the articles that go into more specific methodology. Finally, I will examine the need for the Value Transfer approach in my dissertation.

In a 1992 paper, Costanza and Daly wrote about the idea of natural capital and its relationship to overall sustainability. Their paper provides an in-depth background of natural capital and goes on to illustrate its implications. According to the authors, the term natural capital is based on a more functional definition of capital as "a stock that yields a flow of valuable goods or services into the future (p38)" (Costanza and Daly

1992). What is functionally important is the relation of a stock yielding a flow. Whether the stock is manufactured or natural is in this view a distinction between kinds of capital and not a defining characteristic of capital itself (Costanza and Daly 1992). The authors further divide natural capital into two types. The first type is renewable or active natural capital, while the second is nonrenewable or inactive natural capital. Renewable natural capital is active and self-maintaining using solar energy. Ecosystems are renewable natural capital. They can be harvested to yield ecosystem goods, such as wood but they also yield a flow of ecosystem services like erosion control and recreation when left in place. (Costanza and Daly 1992). Nonrenewable natural capital is more passive. Fossil fuel and mineral deposits are the best examples.

After these definitions, the authors provide the reasons why we need to value natural capital. Their assertion is quite straightforward and compelling. In the past, only manufactured stocks were considered as capital because natural capital was superabundant in that mankind's activities operated at too small a scale relative to natural processes to interfere with the free provision of natural goods and services. Expansion of manufactured and human capital entailed no opportunity cost in terms of the sacrifice of services of natural capital. Manufactured and human capitals were the limiting factors in economic development. Natural capital was a free good (Costanza and Daly 1992).

However, we are in a new era and natural capital has become the limited source. Human economic activities can significantly reduce the capacity of natural capital to yield the flow of ecosystem goods and services upon which the very productivity of human-made capital depends (Costanza and Daly 1992). This is very important point as the classical economic theory assumes that human-made capital is a near-perfect substitute for natural resources. The authors argue that for any given product embodying any given level of technical knowledge, human-made capital and natural capital are, in general, complements, not substitutes (Costanza and Daly 1992).

Finally, the authors link the importance of natural capital to overall sustainability using the difference between growth and development. According to the article, growth is just simple increase, whereas improving efficiency is development. Growth is destructive of natural capital and beyond some point will cost us more than it is worth that is, sacrificed natural capital will be worth more than the extra man-made capital whose production necessitated the sacrifice. On the other hand, development is qualitative improvement that does not occur at the expense of natural capital. There are clear economic limits to growth, but not to development (Costanza and Daly 1992). The authors further argue this implication to the overall sustainability of a society. Weak sustainability is the maintaining intact of the sum of human-made and total natural capital. Strong sustainability is the maintaining intact of natural capital and man-made capital separately (Costanza and Daly 1992). This paper is quite unique and important as it provides the justifications for valuing ecosystem services in economic terms. Societies entering into eras of development and simultaneously confronting limited supplies of natural resources are at a critical juncture for thinking about the values of natural capitals.

More papers discuss the needs for valuing ecosystem services. One, the output of the Ecosystem Valuation Forum held in 1991, involved the work of 15 experts. It covered issues in ecosystem sciences, especially in valuations. According to the authors, the ability to characterize and estimate monetary values of environmental services has grown tremendously since the "Green Book" appeared (Bingham, Bishop et al. 1995). They define what “value” means in the ecosystem valuation discipline. Values are by definition anthropogenic, however, ecosystem values need not derive from human use of the systems or their components. That is, ecosystems may be valuable to people as ecosystems as well as producers of timber and clean water (Bingham, Bishop et al. 1995). Further, ecosystems are dynamic and thus one species may substitute for another species or physical processes can change. Although such changes occur naturally, human actions often cause more rapid or unanticipated changes. Under some circumstances, decision makers analyze the relative costs of alternative means of achieving previously set objectives. For environmental regulations, often the first step is to set "safe minimum standards" which can help ensure that only alternatives that achieve stated objectives are compared (Bingham, Bishop et al. 1995).

In addition, they explain some methodological aspect of ecosystem valuation. Apparently, there are two categories – one relying on observable choices and a second relying on the responses people make to proposed choices. The observable choice is also known as revealed preference, and travel costs or hedonic pricing modeling fall into this category. These methods are preferred by some economists on the grounds that an actual choice demonstrates that the commodity (or service) to be valued has been selected by those whose monetary values are being measured (Bingham, Bishop et al. 1995). On the other hand, proposed choices, also known as stated preference, use contingent valuation or general survey. These methods assume the description or framing of what is to be valued to be a central element in the reliability of the method (Bingham, Bishop et al. 1995). Since ecosystem services are not directly priced through a market system, preferences or willingness-to-pay (WTP) approaches are widely accepted methods. The only problem is that analysts' judgments can influence the monetary estimates inferred from these choices (Bingham, Bishop et al. 1995). There are many articles describing the differences between the methods, which I will review in more detail later.

In 1997, Costanza and 12 other researchers conducted a comprehensive study about ecosystem services' economic values at the global level. This paper, published in *Nature*, is still referenced as one of the classics in the ecosystem science discipline. It estimated the current economic value of 17 ecosystem services for 16 biomes based on published studies and a few original calculations (Costanza, d'Arge et al. 1997). In this study, the researchers did not distinguish any difference between ecosystem goods and services but used them together as ecosystem services. Further, during the estimate, they only included renewable services. This is plausible as renewable services are countable in economic terms. Nonrenewable resources can become priceless as their use is critically limited. Their approach is quite meaningful as it focuses on the changes in quality or quantity of services that may have an impact on human welfare. According to the authors, it is not very meaningful to ask what the total value of natural capital to human welfare may be, nor to query the value of massive, particular forms of natural capital. It is trivial to ask what the value of the atmosphere is to humankind, or what value they place on rocks and soil infrastructure as support systems. Their value is infinite in total (Costanza, d'Arge et al. 1997). Therefore, the authors' assertion is that we only need to assess the services relating directly to humans, and this is the notion that my dissertation tries to follow. Otherwise, estimating services, especially indirect services, will become an intricately complicated procedure.

According to the paper, the value (most of which is outside the market) is estimated to be in the range of US$16–54 trillion ($10^{12}$) per year, with an average of US$33trillion per year for the entire biosphere (Costanza, d'Arge et al. 1997). This is itself a quite impressive result given that the total of global gross national product (GNP) in 1997 was approximately US$18 trillion per year, and still the authors argue that due to the nature of uncertainties, this figure be considered a minimum estimate. According to the authors, many ecosystem services are only substitutable up to a point, and their supply curves probably look more like Figure 1.

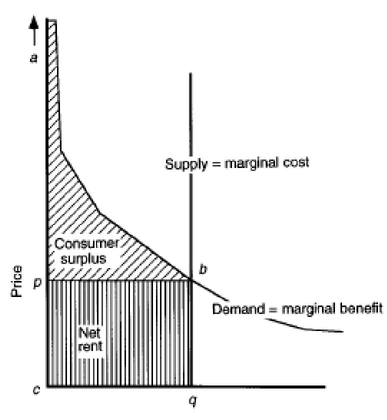


Figure 1 Supply and Demand Curves for Ecosystem Services

This paper yields two additional points that are important. First, the authors clarified that ecosystem services provide an important portion of the total contribution to human welfare on this planet. We must begin to give the natural capital stock that produces these services adequate weight in the decision-making process, otherwise current and continued future human welfare may drastically suffer (Costanza, d'Arge et al. 1997). Although ecosystem valuation is certainly difficult and fraught with uncertainties, it would not be a choice of “to do” or “not to do”. Further, the authors argue that the use of these estimates is for project appraisal, where ecosystem services lost must be weighed against the benefits of a specific project. Because ecosystem services are largely outside the market and uncertain, they are too often ignored or undervalued, leading to the error of constructing projects whose social costs far outweigh their benefits (Costanza, d'Arge et al. 1997). This is very crucial as it explains the importance of including ecosystem services in monetary values during the project investment decisions. Transportation projects especially require such perspective as their impacts are stronger and last longer.

It makes sense then to ask what methods are used to capture the value of ecosystem services. Bingham et al.’s 1995 paper briefly describes valuation methods, which I will review in my section on methodologies. A more recent article, written in 2002, by three scholars, presents a conceptual framework and typology for describing, classifying and valuing ecosystem functions, goods and services in a clear and consistent manner (Groot, Wilson et al. 2002). The authors first define ecosystem functions as “the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly” (Groot, Wilson et al. 2002).

After that, they provide insight into functions and methods. According to the authors, there are four functions of ecosystem: 1) regulation; 2) habitat; 3) production; and 4) information. In addition, an ecosystem has three particular values: 1) ecological; 2) socio-cultural; and 3) economic (Groot, Wilson et al. 2002). Values are estimated according to either direct or indirect market values, and via different estimation techniques. Indirect valuation can be done with five methods: 1) avoided cost; 2) replacement cost; 3) factor income; 4) travel cost; and 5) hedonic pricing. On the other hand, direct valuation utilizes revealed preferences, for instance being the amount of money donated for conservation purposes. An ecosystem's first function, regulation functions are mainly valued through indirect market valuation techniques such as, avoided cost and replacement cost. An ecosystem's habitat function is usually measured with direct valuation. Similarly, production functions are also measured through direct market pricing and factor income methods. Information functions are mainly measured through contingent valuation (cultural and spiritual information), hedonic pricing (aesthetic information), and market pricing (recreation, tourism and science) (Groot, Wilson et al. 2002).

Sinha and Labi 2007 work about transportation decision-making describes the need for valuation in transportation planning. Their book is very comprehensive in that it covers almost every subject in transportation investment decisions. It is chapter 12, which specifically deals with the intersection between transportation and ecosystem services that is of interest here (Sinha and Labi 2007). It first presents the basic concepts of ecological systems and discusses the various mechanisms by which such systems could be affected by transportation developments. The authors also present a set of performance measures and a procedural framework for assessing ecological impacts, focusing on wetlands. Finally, mitigation measures, related federal legislation, and available software packages for ecological impact assessment are discussed.

According to the article, transportation projects create disruptions, and such disruptions can lead to ecological collapse and the demise of many native species. Ecological stability or resilience is a measure of the ability of an ecosystem to recover from such deleterious disruptions (Sinha and Labi 2007). In addition, construction of new transportation facilities leads to decreased area of pervious surfaces, increased runoff, and consequently, increased soil erosion. The components of the physical base—land, air, and water—play vital roles in ecosystem sustainability, and their degradation through transportation construction and operations constitutes a significant loss to the plants and animals that depend on them. Therefore, the selection of transportation infrastructure locations, corridors, and alignments and the design of main and ancillary structures should be carried out to avoid ecologically sensitive areas or to minimize ecological impacts at such areas when they are inevitable (Sinha and Labi 2007). The authors identified four specific evaluation techniques: 1) species calculation; 2) population dynamic modeling; 3) habitat-based evaluation; and 4) gap analysis (Sinha and Labi 2007). Since this article is highly focused on transportation impacts, the above four methods seem appropriate for estimating the value of ecosystem services interfered with by a transportation project.

Another article explaining approaches to utilize in the valuation process is the 2010 study conducted by three scholars about ecosystem service valuation. Using the Millennium Ecosystem Assessment, the authors define ecosystem services as "the benefits that people obtain from ecosystems" and classify its services into supporting, regulating, provisioning, and cultural (Turner, Jones et al. 2010). After defining the process, the authors compare all the methodologies implemented by current studies, amounting to a comprehensive list of nine different methodologies in valuation techniques: 1) market prices; 2) production function; 3) travel cost; 4) hedonic pricing; 5) replacement cost; 6) defensive expenditure; 7) contingent valuation; 8) choice modeling and 9) deliberative monetary valuation (Turner, Jones et al. 2010). Each of the methodologies has advantages and disadvantages, and usage that differs under certain circumstances.

The problem of using such techniques is that all of them use aggregate level analysis; their results may contain problems like double counting or marginality. Like the authors described, at the strategic level, a more macroscale valuation may play an indicative role in decision-making. It can contribute to the further development of indicators of human welfare and sustainability. However, findings from studies of behavioral economics suggest that individuals do not possess consistent preferences for all combinations of private and public goods and that these preferences are not reasonably stable across regions nor independent of the contexts and the mechanisms through which they are revealed. Rather, preferences are more or less endogenous—they change depending on personal experiences, social contacts and geographic context, historical/cultural background, and the type of decision-making process (Turner, Jones et al. 2010). In other words, just as a few articles in transportation project evaluation have revealed, ecosystem valuation needs more location or context-specific approaches. This notion is also partially sustained by Costanza et al.'s 1997 paper. In the next part of this review, I will include more literature that has delved into the methodology of valuation studies.

In 1995, five researchers identified the amount of lands converted from land use changes using a cell-based modeling process (Bockstael, Costanza et al. 1995). This study is quite interesting as it did not estimate the loss of ecosystem in monetary terms, but did provide some instruction for calculating the amount of land loss by land conversions. According to the authors, ecosystems are extremely complex systems whose functions and processes are not easily characterized. Simply describing the factors affecting ecosystems and their reaction to natural and human stresses is particularly troublesome. Hence, this project takes a parallel modeling approach and utilizes advances in computer modeling and spatial data availability to address the trans-disciplinary modeling task in new ways (Bockstael, Costanza et al. 1995). Their study site, the Patuxent watershed, encompassed a total area greater than 589,600 acres, making this study closer to an aggregate level analysis.

Considering the year this work was conducted, technological limitations would indeed have precluded a more micro level analysis. Between 1973 and 1985, the Patuxent watershed experienced a 4.2% (24,763 acres) increase in urban land uses and 2.65% (15,624 acres) and 2.1% (12,381 acres) decreases in agricultural and forests. In other words, in 12 years, about 25,000 acres of lands were converted into urban use, about 88% of which were from either agricultural land use or forests (Bockstael, Costanza et al. 1995). As the authors described, this study would have more impact if the areas could be converted into economic values. Nonetheless, this study is meaningful as it provided a way to calculate the amount of physical losses in ecosystem services.

In addition, the authors identify another limitation to their approach. According to the article, structurally, the disciplines of economics and ecology have much in common. Both analyze and predict the behavior of complex, interrelated systems in which the behavior of individual agents and flows of energy and matter are central, and its dynamics are governed by the allocation of scarce resources among competing agents. However, by evaluating only those components of the ecosystem that have immediate value to individuals, and focusing on short-term changes in the ecosystem, this practice ignores the fact that changes in ecosystems play out over time and space and may indeed be irreversible. Another drawback of the authors' attempts at ecosystem valuation is that the ecosystems tend to be spatially general and broad (Bockstael, Costanza et al. 1995).

More analyses can be found in other literature. In 2006 Naidoo and Ricketts compared the costs and benefits of conserving forests in Australia. Using GIS mapping overlay with spatial BCA, the authors mapped the area of converting forests into developable lands (Naidoo and Ricketts 2006). They first assessed five different ecosystem services: sustainable consumption of bushmeat, sustainable timber harvest, bio-prospecting (value for new pharmaceutical products), existence value, and carbon storage. After that, economic benefits were estimated on an average per-hectare basis. According to the result, carbon storage was by far the most highly valued ecosystem service, with a value of US$378/ha. The next most valuable service was sustainable timber harvest (US$27.60/ha), followed by existence value (US$25/ha), bushmeat harvest (US$15.59/ha), and bioprospecting (US$2.21/ha) (Naidoo and Ricketts 2006). Using this information, the authors created a map of cost-benefit ratios.

This spatial information can inform conservation and land use decisions, but as Naidoo and Ricketts described, it is currently lacking in most conservation planning exercises. The authors found that economic benefits of conservation are substantial and, depending on which services are counted, outweigh costs in certain areas. Ecosystem services often hold significant economic value, but they remain undervalued within policy decisions because they are poorly understood and typically external to markets. As a result, cost-benefit analyses are biased toward development over conservation, and planning efforts miss potential ‘‘win-win’’ areas and associated opportunities to finance conservation in innovative ways (Naidoo and Ricketts 2006). This study is clarifies the trade-offs between conservation and development and deepens our understanding of the economic aspects of conservation. It is hoped that such useful and compelling results will encourage decision makers to realize the synergies between conservation and economic development.

Naidoo, along with researchers Malcolm and Tomasek conducted another study in 2009 that followed a similar valuation scenario in Borneo. This study demonstrates that a rapid assessment of the benefits of standing forests in the highlands of Borneo is feasible and can provide useful and timely information for conservation policy decisions (Naidoo, Malcolm et al. 2009). The authors first used the existing biophysical and economic information to characterize values associated with forests in areas proposed for oil palm plantation development.

According to the authors, the value of most of these ecosystem goods and services does not pass directly through existing markets. Nevertheless they do have tangible economic value, and over the last few decades, economic techniques to calculate these values have been developed and refined. In all instances, not estimating the benefits of ecosystem services can lead to an undervaluation of the natural world by policymakers who may be accustomed to evaluating trade-offs among decisions in terms of dollar values (Naidoo, Malcolm et al. 2009). Using all forested land in the proposed oil palm plantation area for carbon storage, the analysis indicates $1.7 billion to $3.4 billion in hypothetical payments. The authors identified 27 possible scenarios using three ranges - low, medium, and high - of values for forest biomass and carbon price with two ranges of - low and medium - discount rates. Net Present Value (NPV) calculations from these scenarios resulted in a mean carbon storage value of 2.7 billion in U.S. dollars, (± $1.8 billion), with a minimum of $500 million and a maximum of $7.1 billion (Naidoo, Malcolm et al. 2009). Similar to the previous study, the result was also presented in a map format.

The importance of mapping ecosystem services was detailed by Wilson et al. in 2004 in a book chapter covering the background and overall ideas of Value Transfer and ecosystem valuation (Wilson, Troy et al. 2004). According to the article, it is clear that better information about the economic benefits that ecosystem goods and services provide for humans is needed by government, business and civil society to more effectively manage our environmental resources in a sustainable manner (Wilson, Troy et al. 2004). It is obvious that when the economic values of non-market goods and services are left out of decisions, resulting policy tends to overestimate the role of the market values and bias decision-making in favor of immediate development and resource extraction.

The authors also argue that landscapes around the world are comprised of a heterogeneous mix of forests, grasslands, wetlands, rivers, estuaries and beaches that provide many different goods and services to humans. Ecosystem goods and services may therefore be divided into two general categories: (1) the provision of direct market goods or services such as drinking water, transportation, electricity generation, pollution disposal, irrigation and pollination; and (2) the provision of non-market goods or services which include things like biodiversity, support for terrestrial and estuarine ecosystems, habitat for plant and animal life, and the satisfaction people derive from simply knowing that a beach or coral reef exists (Wilson, Troy et al. 2004). How these two different categories are measured? The authors suggest two approaches. First, there is the amount of money people are willing to pay for specific improvements in a good or service, willingness to pay (WTP). Second, there is the minimum amount an individual would need to be compensated for to accept a specific degradation in a good or service, willingness to accept compensation (WAC) (Wilson, Troy et al. 2004). In reality, however, it is very rare to have both WTP and WAC information for various types of ecosystem services. In other words, there is an obvious limitation to measure the market values of ecosystem services, and this is the reason why we need to consider the Value Transfer.

Value transfer is the adaptation of existing valuation information or data to new policy contexts with little or no data. The transfer method involves obtaining an estimate for the economic value of non-market goods or services through the analysis of a single study or group of studies that have been previously carried out to value similar goods or services. Value transfer has thus become a practical way to inform decisions when primary data collection is not feasible due to budget and time constraints, or when expected payoffs are small (Kreuter, Harris et al. 2001). In short, information collected by previous studies of ecosystem services' monetary values can be applied comparably to other study regions. The authors also explain the limitations in using aggregate level analysis. Spatially aggregated measures of geographic features tend to obscure local patterns of heterogeneity (Fotheringham, Brunsdon et al. 2002). Aggregated measures of ecosystem services, while useful, can similarly obscure the heterogeneous nature of the underlying resources that provide those services and yield misleading results (Wilson, Troy et al. 2004).

This article also suggests the shortfalls in recent ecosystem valuation exercises. Assessing the economic value of landscapes is not presented as an alternative to democratic environmental decision-making; rather it is seen as one of many necessary inputs into the decision-making process. While a great deal of economic literature has characterized local spatial variability in demographic and economic terms, there has been considerably less work on the spatial characterization of human-made patches as they relate to environmental processes and impacts. For example, while it is understood that, in aggregate terms, increases in impervious surfaces and road densities due to suburbanization result in increased peak flows, it is not well understood exactly how the configuration and pattern of development and impervious surface affects environmental variables (Wilson, Troy et al. 2004).

This article is very useful and important as it provides the main reasons for using the Value Transfer approach. Since not all services in an ecosystem are measured in WTP or WAC, using the existing estimates under the similar environmental context sounds like a reasonable alternative. In addition, because aggregated measures often hinder measuring the spatial heterogeneity, using more location-specific attributes or estimates under the similar spatial context would make the study result more precise. Finally, as the authors argued, there has been considerably less attention paid to the spatial effect of man-made structures, whereas the impacts of the general population in relation to the overall economic impact have long been pursued. Therefore, estimating the impact of man-made structures to the environmental features is in high demand for more suitable investment decisions.

What are some actual examples of the Value Transfer technique? Several works implement this approach when measuring the monetary value of human activities. For instance, a 2001 article by four scholars reviewed changes in ecosystem services in San Antonio, TX. The objective of the study was to determine whether Landsat satellite images could be used to quantify changes in land-use and ecosystem services due to urban sprawl in Bexar County where San Antonio is centered. Within three watershed covering 141,671 ha of Bexar County, the size of six land cover categories were estimated in the summer of 1976, 1985, and 1991 (Kreuter, Harris et al. 2001). According to the article, monitoring and projecting the impacts of land-use changes is difficult for several reasons. First, monitoring changes at the regional scale (where the impact of land-use changes on ecosystems often become noticeable) is difficult because of the large volume of data and interpretation required. In addition, accurately quantifying the impacts of urban sprawl on changes in ecosystem services is difficult because of the lack of information about the contribution of alternate landscapes to these services. Finally, comparing the impacts of anthropogenic land-use changes with the effects of 'natural' ecosystem changes requires more explicit measures than simple value indices (Kreuter, Harris et al. 2001).

Therefore, the authors referenced Costanza et al.'s 1997 paper, previously reviewed here, and identified the values associated with each land cover. In an effort to make the analysis result more reliable, each value estimate was tested under the sensitivity analysis using elasticity. The most representative biome was used as a proxy for each land cover category, including grass / rangelands for rangelands, temperate / boreal forest for woodland, cropland for bare soil, and urban for the commercial, residential, and transportation categories (Kreuter, Harris et al. 2001). If the ratio of the percentage change in the estimated total ecosystem value (ESV) and the percentage change in the adjusted valuation coefficient (VC) was greater than unity, then the estimated ecosystem value was elastic with respect to that coefficient. If the ratio was less than one, though, then the estimated ecosystem value was considered to be inelastic. Based on results, the San Antonio study area experienced a 4% net decline in the estimated annual value of ecosystem services. At $5.58 hectare per year, the 15-year cumulative total decline in value equated to $6.24 million for the entire study area (Kreuter, Harris et al. 2001). Further, the total ecosystem values estimated for the study area came out to be relatively inelastic.

There are of course limitations in this approach. The authors noted the possibility of misclassification due to seasonal variations in vegetative ground cover at the time that the three satellite data sets were captured. Another possible shortfall is that satellite data from high-resolution detectors have a relatively short history for conducting time series analyses of land-use changes using remotely sensed data. (Kreuter, Harris et al. 2001). Despite such limitations, the method presented here contributes meaningfully to the study of economic value loss incurred by land conversions. Since this paper was written in 2001, there have been significant improvements in satellite image technology, and its use is quite reliable and much more precise than before. Thus, some of the limitations described here could be relieved due to technological advances.

A similar study attempting to measure ecosystem services value was done in 2004 by Herrera Environmental Consultants and Spatial Informatics Group for Maury Island, WA. Elected officials in Maury Island wanted to estimate the level of ecosystem services that could be destroyed by the potential construction of a Glacier Mine. The authors note that typically when estimating the value of an ecosystem, economists have tended to concentrate on those components of the ecosystem that have immediate and obvious value to individuals or society and for which values can be readily estimated. In contrast ecological models have tended to concentrate on aspects of ecosystems that are important to ecosystem functions but that are not directly valued by people. One significant impediment to environmental valuation of natural ecosystems is the lack of knowledge about specific technical linkages between ecosystems and the services they provide to people (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). Therefore, the authors of this report define ecosystem functions as the capacity of natural processes and components to provide goods and services that directly or indirectly satisfy human needs. The concept of ecosystem goods and services used here is therefore inherently people-oriented; it is the presence of human beings that enables the translation of basic ecological structures and processes into value-laden entities (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004).

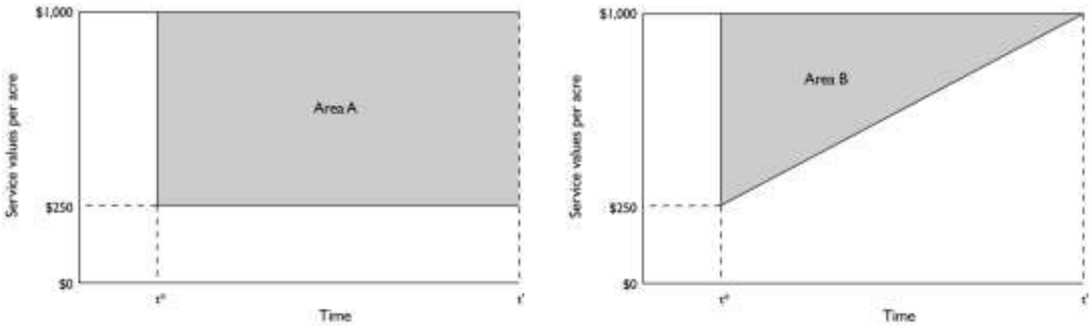
Further, the authors articulate why they are using the Value Transfer approach. While a fair amount of research has been done on the economic value of ecosystem services globally, little peer-reviewed work has been done to explicitly estimate the economic value of ecosystems located in Puget Sound itself, or even in Washington State. Because relatively little ecosystem service valuation research has been done locally, values needed to be "transferred" from outside the state to the Maury Island site. To achieve this, the project team used secondary analysis of published results drawn from the peer-reviewed economic literature. Secondary analysis of available valuation literature is a 'second best' strategy that can nevertheless yield very important information in many scientific and management contexts. When analyzed carefully, information from past studies published in the literature can form a meaningful basis for directing environmental policy and management. Given the expense and time associated with estimating values of nonmarket natural resources and services, benefits transfer is a reasonable technique by which to determine such values. Transfer methods may be particularly useful in management and policy contexts in which estimates of economic benefits not generated by an original study may be sufficient to make a judgment regarding the advisability of a management action or project (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). Results from a value transfer application are less accurate than primary valuation analyses, yet they are clearly justified under practical circumstances where primary analysis is out of reach and precision is less critical to the decision-maker. Transfer studies provide an economical way to conduct valuation research when a full-fledged empirical study is not practical or necessary (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004).

The authors also describe the reason why location-specific measures should be implemented. According to the article, aggregated, global measures of ecosystem services are useful as approximations of the importance of ecosystem goods and services, but they can actually obscure the heterogeneous nature of the underlying ecological structures and functions that provide those services and lead to misleading results (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). This notion was also supported by Wilson and other co-authors. Such an aggregated measure does not tell us whether those cover types are distributed evenly throughout the nation or are all clustered in one region. Obviously, those two possibilities have significantly different ramifications for resource use and landscape management. Not only does a clustered pattern of wetlands imply that some regions have more wetlands than others, but it also means that the social cost of losing one wetland is much higher in the areas of scarcity than in the areas of clustering (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004).

Thus, for this project ecosystem service valuations were made spatially explicit by disaggregating the Maury Island landscape and its near shore environment into constituent land cover types at the parcel scale (i.e., individual land parcels were identified and associated ecosystem service values estimated). This kind of spatial disaggregation greatly increases the potential for management applications of ecosystem service valuation by allowing decision-makers to map and visualize the explicit location of ecologically important landscape elements and overlay them with the ecosystem services that people value. Disaggregation is also important for descriptive purposes, for the pattern of variation is often much more telling than any aggregate statistic (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004).

The paper then describes the different use of discount rates. The purpose of the analysis is to quantify the loss from the time the site is developed until the resources recover or, if the resources are not expected to recover, to a specific point in the future. The same measures of lost service values and discounting methodology were therefore used for the two development scenarios: permanent injury and natural recovery (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). This is quite useful as ecosystem services can be distinguished as one or the other, and their values would clearly differ. Figure 2 indicates the differences between the two. As can be seen, if permanent injury is assumed, the total loss of the same ecosystem service is $9,814 for 20 years. On the other hand, if natural recovery is assumed, then the total costs are

$7,015 for the same period of time. Of course, how analysts define the recovery rate will change the overall results, but this method allows for more precise estimations of the values.



Year	Uninjured Value of Provided Services	Injured Value of Provided Services	Annual Value of Lost Services	Present Value of Lost Services
0	$1,000	$1,000	$0	$0
1 (t*)	$1,000	$250	$750	$750
2	$1,000	$250	$750	$734
3	$1,000	$250	$750	$680
4	$1,000	$250	$750	$648
5	$1,000	$250	$750	$617
6	$1,000	$250	$750	$588
7	$1,000	$250	$750	$560
8	$1,000	$250	$750	$533
9	$1,000	$250	$750	$508
10	$1,000	$250	$750	$483
11	$1,000	$250	$750	$460
12	$1,000	$250	$750	$439
13	$1,000	$250	$750	$418
14	$1,000	$250	$750	$398
15	$1,000	$250	$750	$379
16	$1,000	$250	$750	$361
17	$1,000	$250	$750	$344
18	$1,000	$250	$750	$327
19	$1,000	$250	$750	$312
20 (t')	$1,000	$250	$750	$297
Total	$21,000	$5,750	$15,000	$9,834

Year	Uninjured Value of Provided Services	Injured Value of Provided Services	Value of Lost Services	Present (discounted) Value of Lost Services
0	$1,000	$1,000	$0	$0
1 (t*)	$1,000	$250	$750	$750
2	$1,000	$269	$731	$731
3	$1,000	$289	$711	$677
4	$1,000	$311	$689	$625
5	$1,000	$335	$665	$574
6	$1,000	$361	$639	$526
7	$1,000	$388	$612	$480
8	$1,000	$417	$583	$435
9	$1,000	$449	$551	$391
10	$1,000	$483	$517	$350
11	$1,000	$520	$480	$309
12	$1,000	$560	$440	$270
13	$1,000	$602	$398	$233
14	$1,000	$648	$352	$196
15	$1,000	$697	$303	$161
16	$1,000	$750	$250	$126
17	$1,000	$807	$193	$93
18	$1,000	$868	$132	$60
19	$1,000	$934	$66	$29
20 (t')	$1,000	$1,000	$0	$0
Total	$21,000	$11,941	$9,059	$7,815

Figure 2 Permanent Injuries vs. Natural Recovery

Using the standard discount rates defined by the White House's Office of Management and Budget, the total values were calculated. According to the article, the annual value of the existing ecosystem goods and services within the Maury Island project area is estimated to be $22.68 million per year. Adding these annual values for a period of 100 years and discounting the total to account for a Net Present Value (NPV), the ecosystem goods and services are estimated to amount to between $649 million and $831 million in 2004 dollars, depending upon the discount rate selected. Developing the Glacier Mine would reduce the NPV of Maury Island ecosystem goods and services by between $0.9

million and $1.1 million (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). This is based on the assumption that the mine would be remediated during the 35-year mining process and that disturbed areas would be 80% restored within 10 years after mining operations are finished. In other words, if the mine operates more than 35 years or the disturbed ecosystems are not restored within 10 years after the mining process, then this calculation will be a very conservative measure.

This paper is an excellent example of how the Value Transfer method is utilized in a real research project. The authors provided reasoning behind using the Value Transfer approach, adopting disaggregated measures, and categorizing the services into permanent injury or natural recovery. If used with a proper care, the outcomes will provide a long-term financial flow of infrastructure investments. Not only by considering the direct costs, but also by estimating the indirect costs, especially for environmental loss, the Value Transfer method helps make more balanced and sustainable decisions in investments.

About 20 articles covering ecosystem valuation have been reviewed. As can be seen, natural capital can barely be replaced by man-made capital and thus, its supply is limited (Costanza, d'Arge et al. 1997). In this sense, achieving sustainability is a difficult task as it requires diverse spectrums of efforts. Nonetheless, as far as the environment is concerned, valuing ecosystem services and understanding their values to human life will be an important task. Like Costanza and Daly described, it is imperative that developing societies confronting the limited supply of natural resources, consider the values of natural capitals (Costanza and Daly 1992). Otherwise, all investment decisions will be based upon direct market values and we can only expect physical growth. Yet, as ecosystem services are markedly diverse and indirect by nature, explicitly defining their services is often met with obstacles. Therefore, we need only to assess those services related to humans (Costanza and Daly 1992; Costanza, d'Arge et al. 1997).

There are two reasons to include ecosystem valuation in decision-making process. First, we must begin to allot the natural capital that produces services adequate stock in the decision-making process. Otherwise current and continued future human welfare may drastically suffer (Costanza, d'Arge et al. 1997). In addition, ecosystem services should play a role in project appraisal, but as they are largely outside the market and uncertain, they are too often ignored or undervalued, leading to erroneous consent of construction projects in which social costs far outweigh their benefits (Costanza, d'Arge et al. 1997). This point is especially meaningful to a transportation project as the impact of transportation infrastructure is stronger and lasts longer.

The need for a specific economic valuation of ecosystem services in the decision-making process is found throughout the literature as well. As Wilson et al. described in their 2004 paper, it is obvious that when the economic values of non-market goods and services are left out of decisions, resulting policy tends to overestimate the role of the market values and bias decision-making in favor of immediate development and resource extraction (Wilson, Troy et al. 2004). In addition, Herrera Environmental Group and Spatial Informatics Group explained that when estimating the value of an ecosystem, economists have tended to concentrate on those components of the ecosystem that have immediate and obvious value to individuals or society and for which values can be readily estimated. In contrast, ecological models have tended to concentrate on aspects of ecosystems that are important to ecosystem functions but that are not directly valued by people (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004).

The several techniques adopted by the ecosystem valuation disciplines can be summarized into nine: 1) market prices; 2) production function; 3) travel cost; 4) hedonic pricing; 5) replacement cost; 6) defensive expenditure; 7) contingent valuation; 8) choice modeling and 9) deliberative monetary valuation (Turner, Jones et al. 2010). The problem of those methods is that most of them utilize aggregate level datasets and thus, their outcomes generally ignore the spatial heterogeneity (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). Methods utilizing only those components of the ecosystem that have immediate value to individuals and that focus on short-term changes in the ecosystem ignore the fact that changes in ecosystems play out over time and space and may indeed be irreversible. In other words, a drawback of the existing attempts to value ecosystems is that they tend to be spatially general and broad (Bockstael, Costanza et al. 1995), a notion also sustained by Costanza et al.'s 1997 paper.

According to Herrera Environmental Consultants, aggregated, global measures of ecosystem services are useful as approximations of the importance of ecosystem goods and services, but they can actually obscure the heterogeneous nature of the underlying ecological structures and functions that provide those services and provide misleading results (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). Such an aggregated measure does not tell us whether those cover types are distributed evenly throughout the nation or are all clustered in one region. Obviously, those two possibilities have significantly different ramifications for resource use and landscape management. Not only does a clustered pattern of wetlands imply that some regions have more wetlands than others, but it also means that the social cost of losing one wetland is much higher in the areas of scarcity than in the areas of clustering (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004). In addition, it is very rare to have both Willingness-To-Pay (WTP) and Willingness-To-Accept (WTA) information for various types of ecosystem services in reality. In other words, there is an obvious limitation to measure the market values of ecosystem services, and this is the reason why we need to consider the Value Transfer (Wilson, Troy et al. 2004).

Value transfer is the adaptation of existing valuation information or data to new policy contexts with little or no data (Wilson, Troy et al. 2004). The transfer method involves obtaining an estimate for the economic value of non-market goods or services through the analysis of a single study or group of studies that have been previously carried out to value similar goods or services. Value transfer has thus become a practical way to inform decisions when primary data collection is not feasible due to budget and time constraints (Kreuter, Harris et al. 2001). When analyzed carefully, however, information from past studies published in the literature can form a meaningful basis for directing environmental policy and management. Given the expense and time associated with estimating values of nonmarket natural resources and services, benefits transfer is a reasonable technique by which to determine the associated environmental values. Not only by considering the direct costs, but also by estimating the indirect costs, especially for environmental loss, the Value Transfer technique helps make more balanced and sustainable decisions in investments. This is the point of my dissertation aiming to incorporate the Value Transfer method into the TCA and the alternative evaluation process.

3. RESEARCH DESIGN

3.1 Research Scope & Hypotheses

This dissertation aims to target the very specific point where transportation planning, SDSS, and ecosystem management all intersect. Not many studies have been conducted that cover all three aspects in one comprehensive analysis, although much of the existing literature specifies the need to inclusively analyze all three measures when making related decisions (Crossland, Wynne et al. 1995; Janic 2003; Annema, Koopmans et al. 2007; Brucker, Macharis et al. 2011). In this section, I will describe the limits of the existing research based on their current intersection and relevant gaps with specific research hypotheses.

3.1.1 1st Research Scope - Intersection I (Transportation & DSS)

As can be seen in Figure 3, there are particular overlapping points in the three disciplines: 1) transportation planning; 2) decision support system (DSS); and 3) ecosystem management. In what I have labeled Intersection I, there are a variety of studies utilizing DSS in transportation investment decisions. However, the biggest shortcoming of these studies is a lack of precise alternative generation and interpretation. In some cases alternative generation is not feasible, whereas alternative ranking and comparison are not possible in other cases (Crossland, Wynne et al. 1995; Ascough, Rector et al. 2002; Uran and Janssen 2003; Malczewski 2006).

The other shortcoming in the existing DSS or Multi-Criteria Decision Analysis (MCDA) systems is in their weighting process. Virtually all models depend heavily on the opinions of experts or professionals in the weighting process, and thus are claimed to be somewhat arbitrary or vulnerable to the decision-making environment. As briefly mentioned in Section 2.1, the availability of expert knowledge is sometimes limited and complete consensus among experts is often difficult to achieve (Basnet, Apan et al. 2001; Arampatzis, Kiranoudis et al. 2004).

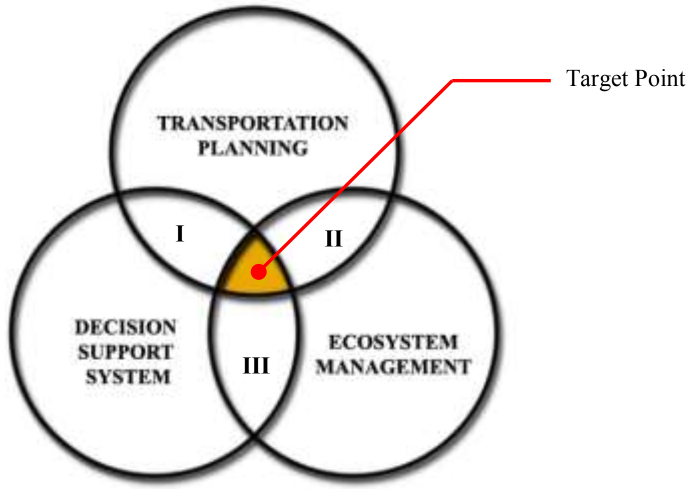


Figure 3 Diagram of Research Target

Further, as the number of variables increase, external factor weights becomes less sensitive and it is hard to capture the differences between route outcomes. One of the strengths of using DSS is its diversity of inputs. If we cannot distinguish the effects between factors because of a systematic error, the final decision will be highly unreliable (Uran and Janssen 2003; Malczewski 2006).

To overcome these limitations, the model proposed here utilizes the factor analysis technique, a statistical approach treating geographic datasets as stated preference. Using confirmatory factor analysis, each variable can be grouped together to identify its common underlying structure. For example, inputs such as wetlands, hydrology, and floodplain all relate to water resources to a certain degree, and thus they could be factored into one group. Although it was close to a conceptual clustering as an explanatory factor analysis (EFA) was implemented, I was able to cluster variables into a few groups and extract routes accordingly in the 2011 Texas Urban Triangle project. Variables such as population density, roads, and land use tend to reside in one group, while the similar characteristics of vegetation, geology, and slope have make for another group.

This step supports a reasonable foundation for the existing weighting process. As the number of items to be externally weighted is reduced, their effects on the final routes become more meaningful. Instead of using 40 different factor weights, we can utilize a fewer number of weights based on the number of groups created. Another advantage of this methodology is then its ability to yield alternative route scenarios. Once the factor analysis is done and a number of factor groups are obtained, users can expect to have route options that are particularly sensitive to each group's underlying characteristics.

3.1.2 2nd Research Scope - Intersection II (Transportation & Ecosystem Services)

As briefly noted, many transportation studies utilize benefit-cost analysis in transportation investment decisions. Costs include fixed (internal) expenditures such as construction, maintenance, or operation costs. Since the 1990s, however, social (external) costs are often measured and included as a variable in research projects (Levinson, Kanafani et al. 1999; Janic 2003; Lu and Morrell 2006). Transportation projects analyzing externalities usually contain social costs such as congestion, air pollution, and noise. Environmental impact has generally been conducted as a separate study, without monetary terms. With technological advances such as the implementation of GIS, however, it is possible to describe environmental impacts in quantitative terms. Even though we now have diverse ways to measure the overall environmental costs associated with particular projects, inclusion of direct and indirect environment costs in the transportation project appraisal process still lacking. Several studies discussed in the literature review stipulate this need although most of them do not meet it (Wilson, Troy et al. 2004; Annema, Koopmans et al. 2007; Sinha and Labi 2007; Brucker, Macharis et al. 2011).

This demand can be relieved by including an ecosystem valuation approach in the final evaluation process. By doing so, the final routes become more comprehensive and interpretable. For instance, a route with more emphasis on water resources would have a different monetization value in terms of ecosystem services compared to a route highlighting economy of scale. To conduct this type of analysis, several indicators need to be established that can be used to measure both the economic and environmental costs of each route. There are various studies describing the costs of ecosystems (Costanza and Daly 1992; Costanza, d'Arge et al. 1997; Cheng, Gaebel et al. 2001; Kreuter, Harris et al. 2001; Wilson, Troy et al. 2004; Brucker, Macharis et al. 2011). One fine example is the economic value of wetland conversions. Most studies explain that the annual cost of converting wetlands to an impervious surface is approximately $55,000/hectare/year (Woodward and Wui 2001; Sinha and Labi 2007).

In this sense, if a particular route crosses more wetlands than alternative options, the total costs will differ to a larger degree. These environment costs using various studies are articulated and adopted with an approach called value transfer in the ecosystem valuation discipline (Kreuter, Harris et al. 2001; Wilson, Troy et al. 2004; Troy and Wilson 2006). More specific attributes for each category are explained in Section 3.4.4.

3.1.3 3rd Research Scope - Intersection III (DSS & Ecosystem Services)

Ecosystem valuation has long been of great interest to many scholars. Since the beginning of the 1990s, many studies measured diverse benefits that ecosystem services bring to society (Costanza and Daly 1992; Costanza, d'Arge et al. 1997; Groot, Wilson et al. 2002; Naidoo and Ricketts 2006; Turner, Jones et al. 2010). However, because of methodological limitations, most of them deal with macro level analyses, closer to a global level. Typical analyses involved “top-down” approaches and are less sensitive to local changes. Recently, ecological scientists started to focus on location-specific measures, and GIS accelerated such innovations. With the GIS land cover analysis and value transfer approach, a “bottom-up” decision-making process is feasible, for which many studies describe there being a need (Kreuter, Harris et al. 2001; Wilson, Troy et al. 2004; Malczewski 2006).

This is also true in most suitability analyses. Suitability analyses utilizing SDSS and environmental impact assessments have long used a point system instead of a monetization process. This is largely due to the lack of methods precisely capturing the monetary values of each ecosystem service. Since the beginning of the 1990s, however, with an increased interest in ecosystem valuation, measuring the aggregate level of ecosystem services became feasible. Recently, many articles have been conducted to measure the monetary values of global ecosystem services (Costanza and Daly 1992; Bingham, Bishop et al. 1995; Bockstael, Costanza et al. 1995; Costanza, d'Arge et al. 1997; Cheng, Gaebel et al. 2001; Naidoo and Ricketts 2006).

One shortcoming of the aggregate level study is its lack of precision. During the literature review process, I found a number of studies requiring more location-specific or project-specific ecosystem valuation approaches (Bingham, Bishop et al. 1995; Wilson, Troy et al. 2004; Troy and Wilson 2006; Annema, Koopmans et al. 2007). The suggested process in this dissertation contains location-specific valuation measures by including monetary values in each route's total costs.

Using different route options created with the SDSS, this study identifies the types of ecosystem services influenced by each route option, and its impacts are calculated in monetary terms. The outcome is the comparison of the total cost analysis. If done properly, this dissertation will significantly reduce the existing gaps between the DSS and ecosystem management disciplines.

3.2 Research Hypotheses

Based on three particular research scopes, research hypotheses are drawn to prove that the suggested methodology in this study covers the gaps in SDSS, transportation project evaluation, and ecosystem valuation disciplines. The central hypothesis of this study is that a high-speed rail (HSR) route with more environmental features incorporated at the beginning of the planning stage will offset the short-term expenditures with higher benefits in the long run. By incorporating ecosystem valuation measures, and more specifically, by using the value transfer method in the route interpretation process, users will see the financial tradeoffs in the final routes. In other words:

- **Hypothesis#1-1:** *The routes optimized with environmental variables such as water or ground resource variables, consume less total cost than the route options optimized with socio-economic or built-environment variables.*

- **Hypothesis#1-2:** *The more inclusive economic values of environmental services offer a lower total cost due to the economic benefits from the preserved ecosystem features.*

The next are research questions about the suggested SDSS. The inputs variables in the proposed SDSS are the largest contributors to the final routes. In addition, as these inputs are the independent variables of this dissertation, their use and application are other important aspects. Furthermore, the significance of the grouping process also needs to be tested. As mentioned earlier, utilization of factor analysis will uncover the underlying structures of inputs and it will also be tested for statistical significance. Using a confirmatory factor analysis, underlying structures of input variables will be verified with statistical significance.

- <u>Research Statement#2-1:</u> Socio-demographic variables such as Population Density, Occupancy Rate, and Job Density variables load together as one factor.

- <u>Research Statement #2-2:</u> Built-environment variables such as Land Use, Noise, and Road Network variables load together as one factor.
- <u>Research Statement #2-3:</u> Ground resources variables such as Aquifer, Geology, and Precipitation Rate variables load together as one factor.

- Research Statement #2-4: Water resources variables such as Hydrologic Units, Floodplain, and Wetlands variables load together as one factor.

- Research Statement #2-5: Green space variables such as Productive Farms, Vegetation Covers, and Slope variables load together as one factor.

The last questions are about result interpretation. If the suggested hypotheses and research questions on the factor analysis turn out to be significant, the total suitability scores as well as the total costs of each route should differ to a certain degree. In other words, each corridor possesses particular implications.

- Research Statement #3-1: Routes weighted on socio-demographic and built-environment factors consume less land acquisition, operation costs, and construction costs than the other routes.

- Research Statement #3-2: Routes weighted on ground resources, water resources, and green space factors consume less environmental costs than the other routes.

As can be seen in the hypotheses and research questions, this dissertation aims to provide a more advanced decision support system by incorporating three different aspects into one comprehensive analytic system; to propose an alternative view on transportation project evaluation; to calculate all associated costs to obtain more sustainable views on long-lasting infrastructure investment decisions; and to find any possibility of participatory-GIS in the overall decision-making environments.

3.3 Research Framework

Figure 4 illustrates how each analysis step is conceptually related to the overall objective. The first half presents the implementation of GIS-based SDSS and the statistical significance of inputs with factor analysis. For the second half, cost comparisons are conducted. The total costs are calculated from three particular aspects: 1) construction; 2) operation; and 3) environment. Based on the overall suitability scores and the total costs, the most sustainable HSR route is selected.

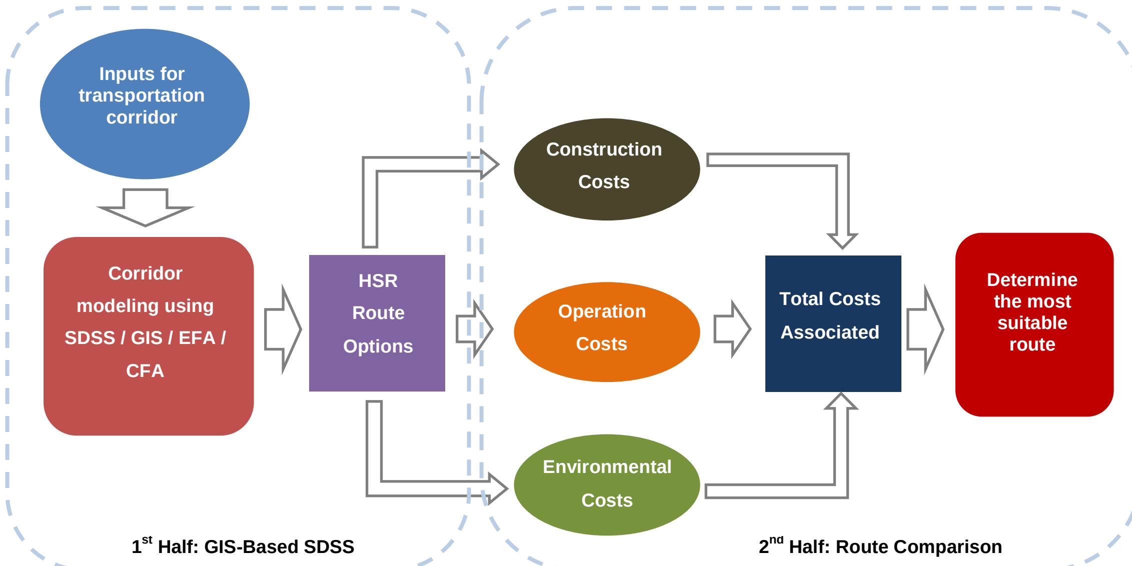


Figure 4 Simplified Research Frameworks

3.3.1 Detailed Research Framework & Hypotheses Testing

Figure 5 details how variables are related to the overall research goal and framework. The main independent variables of this framework are the planning variables that need to be extensively considered for a new HSR route within the State of Texas. The TUT research already identified 44 different inputs during the research process and about 11 of them were utilized in the previous studies (Neuman, Bright et al. 2010; Kim, Wunneburger et al. 2011). As this research shares its foundation with TUT, these 11 inputs will still be used and more variables will be included based on discussions with the committee members. This is a very important step as it allows the possibility of more participation from the users.

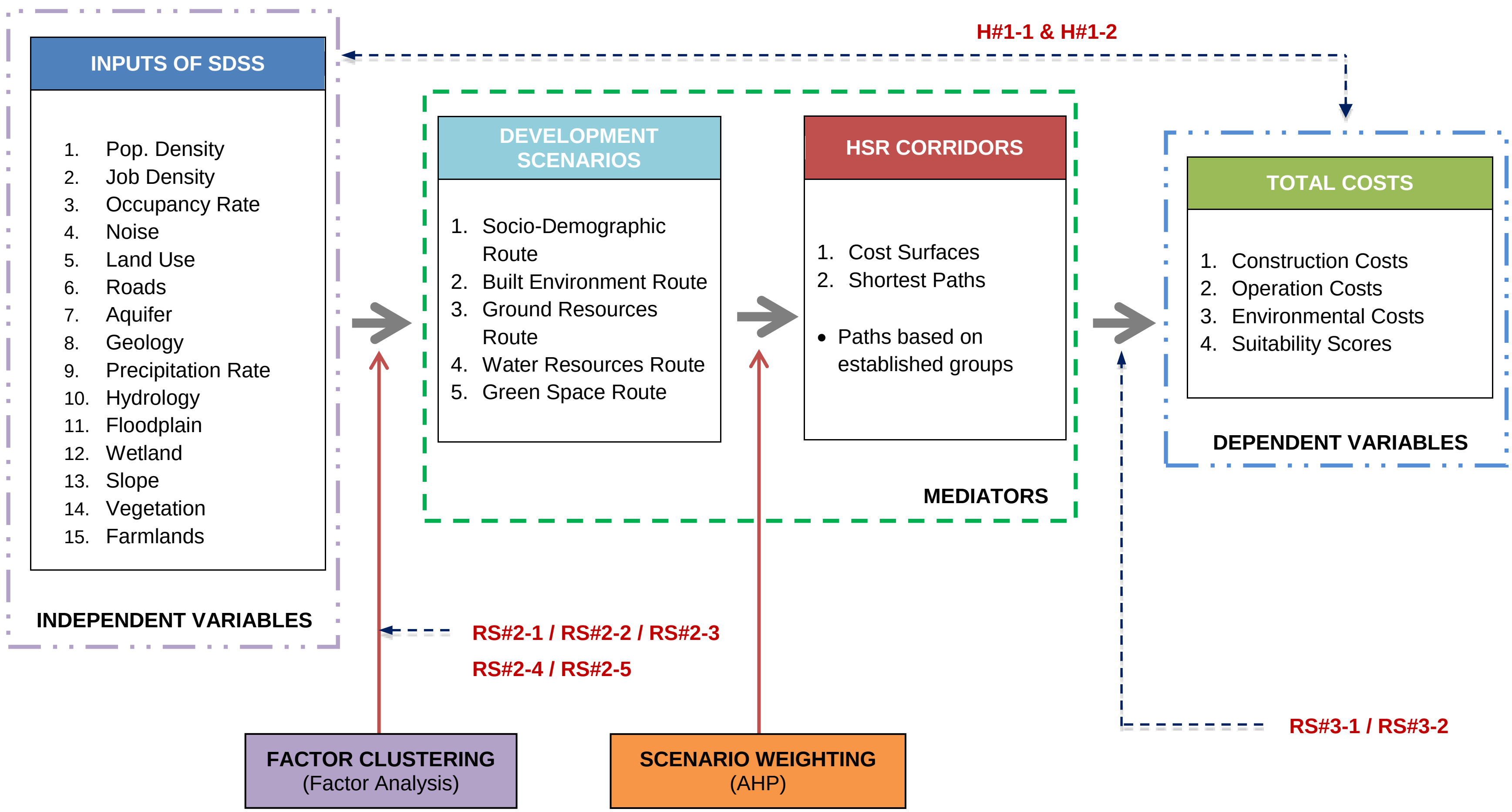
There are two particular steps in this research where users can actively express their opinions, and this variable selection is one. If done properly, decision criteria and considerations are set up with inputs from both the experts and the general public at the beginning of the decision-making process. Once input variables are selected, a confirmatory factor analysis (CFA) is conducted. Accordingly, corresponding groups will be extracted based on the underlying structures of the variables, and the routes are extracted with a raster-based GIS modeling approach. Finally, routes are interpreted with their total costs, and the most suitable one is selected.

The previous TUT study boundary was conducted to test HSR routes between San Antonio and Austin, whereas this study focuses on the routes between Houston and Austin. This could become a part of the "T-Bone" HSR route and may be a more versatile route than the one between Dallas and Houston. Precise routing for the T-Bone line is still in discussion at the moment. Some organizations place it from Houston to Temple (Texas High Speed Rail and Transportation Corporation 2011), whereas others put it in between Austin and Houston (Federal Railroad Administration 2011). In this study, I choose the latter as its total length is longer, over 150 miles and the final routes would have more sensitivity to the overall inputs and the SDSS environment.

As can be seen, the independent variables create different groupings with a CFA. During the grouping process, the second part of research statements (#2-1, #2-2, #2-3, #2-4, and #2-5) are tested. If done properly, a few different groups are created based on each variable's underlying structure. One big advantage of having groups instead of a large number of factors is increase in sensitivity. As the number of items for external weights reduces, effects of weights on routes become more sensitive. Instead of using 40 different factor weights, we can utilize less number of weights based on the number of groups created. The other advantage resides on its ability to draw possible scenarios. Once the factor analysis is done and obtained groups of factors, users can expect to have a route option that is particularly sensitive to each group's underlying characteristic. If we treat internal classification (internal weights) as a survey question and receive responses from the users, such information can be regarded as a stated preference survey. In other words, we could utilize internal classification process as the base survey questionnaires, and then perform a statistical analysis. By doing so, the grouping process will become more logical and scientifically reliable.

After testing the statistical significance of each group, routes are extracted using the cost surface and shortest path analysis in ArcGIS v. 10. To differentiate each variable's implication to the final routes, weights will be given to each group. Different weights create different suitability surfaces and optimal routes.

The final step concerns route interpretation. As previously mentioned, four parameters are compared: 1) construction costs; 2) operation costs; 3) environmental costs; and 4) suitability scores. During this step, research statements #3-1 and #3-2 are tested. Finally, a total cost is compared to test the main hypotheses#1-1 and #1-2, and the most suitable and sustainable route is selected.



(RS: Research Statement / H: Hypothesis)

Figure 5 Detailed Research Frameworks

3.4 Research Models & Datasets

This dissertation implements three modeling techniques. First, the overall analysis is done using ArcGIS version 10. Specifically, a raster-based GIS modeling process is utilized. Testing the grouping in terms of statistical significance will be done with factor analysis. Of the two types of factor analysis, confirmatory factor analysis (CFA) will be implemented. Finally, calculating environmental features in monetary terms is done using an approach called value transfer. Value transfer has a specific meaning and implication in the ecosystem science discipline and is extensively explained in the literature review section.

3.4.1 Raster-Based GIS Modeling

Unlike vector-oriented methodologies, raster-based GIS modeling converts all the necessary information into a raster format, meaning that all information is stored in grid cells (pixels). Therefore, a map is not just a simple map representing the current circumstances; it contains relevant information in each pixel. Further, each pixel can be manipulated to create new information by using simple procedures such as map algebra or reclassification.

Raster-based modeling is especially powerful when new information is in demand based on existing conditions. By converting all data sets into raster formats, we obtain new information at the pixel level. For example, if we say that a population density of less than 10 (10 people/acre) equals a suitability score of 2, then all the pixels with a population density less than 10 are converted into a score of 2. This process is called reclassification and is the first step in creating suitability surfaces.

The second process involves the summation of all raster maps. Pixels can be manipulated to create new information with simple mathematical approaches such as the “Raster Calculator” in ArcGIS. Accordingly, suitability surfaces are created with the calculated weights and a unified internal scale. These suitability surfaces are in a 30 meters x 30 meters grid format with the scores in each cell. Via internally classified raster maps and their external weights, the final cost surfaces are created. If written in a mathematical way,

$$\text{Suitability Surface for a Preferred Scenario } k = \sum_k \boldsymbol{w_k} \cdot \boldsymbol{x_k} + \sum \boldsymbol{w} \cdot \boldsymbol{x} \qquad (1)$$

Where w_k: external weight for the variables in preferred group k

x_k: value of grids in group k

w: external weight for the variables in the other groups

x: value of grids in the other groups

The final step is the shortest path analysis. Using the shortest path analysis, we extract the most suitable pixels and connect them to generate the optimal route. This function finds the pixels with the least possible scores between the two points. After setting up the origin and destination, ArcGIS seeks for the least possible scores around each proceeding pixel. The least possible scores are continuously identified and connected until the path reaches its final destination. Figure 6 represents how ArcGIS identifies the least possible pixels and connects them into one single route.

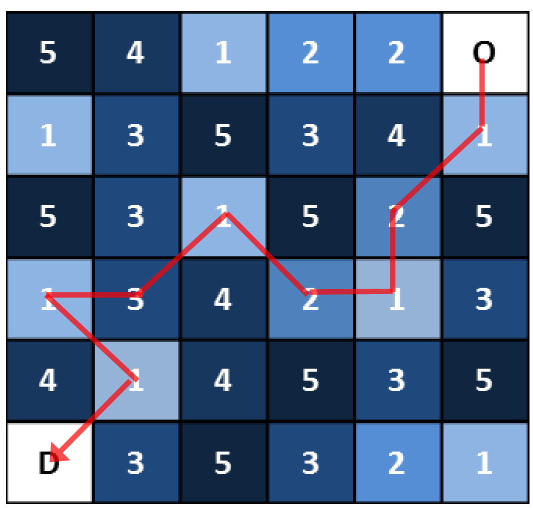


Figure 6 Shortest Path Identification

Station locations can become highly politicized, and locating stations involves a different set of decision-making procedures and requires in-depth research. For these reasons, the researchers in the previous TUT study decided to set the departure and destination points to the two major airports. Following this precedent, this dissertation also sets departure and destination points to each city's airport in an effort to avoid any political conflicts and to concentrate on the route-modeling and interpretation process.

3.4.2 Factor Analysis

Factor analysis is a statistical method to describe the variability in observed variables in extent to their underlying, undiscovered structures (Brown 2006). Using factor analysis, it is possible to say that variations in a few different observed variables mainly reflect the variations of one common ground. Unlike the term "factor" we use in SDSS, "factor" in factor analysis indicates a particular meaning. Factor refers to the underlying structure that variables commonly possess (DeCoster 1998). For example, if one has done a factor analysis with wetlands, floodplain, and hydrology and obtained a statistically significant result, then we could say, in factor analysis terminology, those three items statistically load on one factor. A factor in factor analysis indicates the common underlying structure (characteristics) of selected variables. In SDSS, what we call factors would be better interpreted as items, and groups or clusters as factors.

There are two types of factor analysis – explanatory factor analysis (EFA) and confirmatory factor analysis (CFA). EFA enables users to draw common patterns among observed variables and allows for extracting groups (DeCoster 1998). In other words, EFA is generally done with an analyst's conceptual imagination. Once a possible grouping is drawn with the EFA, we confirm such a grouping in terms of statistical significance with CFA. CFA produces many indicators to confirm that the grouping is statistically significant (DeCoster 1998; Brown 2006; Suhr and University of Northern Colorado 2006). If a certain type of indicator is met with the conventionally accepted statistical allowance, then we confirm the grouping structure is statistically reliable, and use them in the SDSS process.

There are a few different rules of thumb in CFA. For example, it would be statistically safe to say that one factor (group) should have at least three items (variables) to indicate the underlying structure. In other words, there will be issues such as cross loadings - one variable shows its variation to more than one ground, or insufficient factor loadings and need to drop few variables. However, there are tactics to relieve such difficulties in a model. In my opinion, an issue like double counting would be better dealt with in the item selection process, rather than at the factor analysis stage. With extensive deliberation and discussion with the committee members, items will be carefully selected to minimize any anticipated issues in the CFA and the SDSS at large.

Table 2 Explanatory Factor Analysis Results of 2011 TUT Project

No.	Group Name	Variables
1	**Demographic Group**	Density 2000 / Density 2010 / Noise
2	**Built Environment Group**	Parcel Values / Road Network / Land Use
3	**Water Resources Group**	Floodplain / Hydrology / Wetlands
4	**Farm Conservation Group**	Animal Sales / Crop Sales / No. of Farm Operators
5	**Ground Resources Group**	Vegetation / Geology / Slope (Grade)

During the TUT project, researchers utilized explanatory factor analysis, and created five different groups with 13 variables. Table 2 indicates the outcome. As can be seen, variables with similar underlying characteristics load on the same group and each group's implication to the overall built environment is different. For example, demographic group is composed of variables such as population density, land use, and noise. In this case, we can say the route based on this group causes less conflict in relocating people; consumes less cost in land acquisition; and creates fewer nuisances to nearby residents. Using this underlying logic for each group, corresponding HSR characteristics route are extracted and interpreted.

In this study, I utilize CFA to confirm the structures of inputs and reveal their similarities in creating a number of groups. If the statistical allowances are met, the results improve the variations in route options, and increase the sensitivities in the external weighting process. If the statistical allowances are unsatisfied, then I shift to an EFA and identify the underlying structure.

3.4.3 Value Transfer

Value transfer stands for one particular methodology in ecosystem valuation studies. Although location-specific or micro-level valuation studies are in demand, they generally require more intensive datasets and precise measurements than the studies at an aggregate level (Wilson, Troy et al. 2004; Ganz, Saah et al. 2007). In other words, data availability usually becomes an issue in micro-level studies. To overcome such limitations and keep the focus on project-specific measures, researchers in ecosystem science suggest a second-hand method: value transfer.

Value transfer is the adaptation of existing valuation information or data to new policy contexts with little or no data (Desvousges, Johnson et al. 1998). The transfer method involves obtaining an estimate for the economic value of non-market goods or services through the analysis of a single study or group of studies that have been previously carried out to value similar goods or services (Wilson, Troy et al. 2004). When conducting a primary research work where accurate data collection is not feasible, value transfer represents a meaningful “second-best” strategy and the starting point for the evaluation of environmental features (Troy and Wilson 2006).

A few studies have used the value transfer method to capture the monetary values of ecosystem services. Most of them utilized GIS-based land cover datasets to analyze the amount of land covers that was replaced by man-made structures. Specifically, studies utilizing the value transfer methods have been particularly concerned with the encroachment of urban areas into rural. To calculate the monetary values that have been lost because of indiscriminate land conversion, the value transfer method along with land cover datasets in GIS are often utilized (Kreuter, Harris et al. 2001; Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004; Troy and Wilson 2006; Ganz, Saah et al. 2007). Researchers first find the economic values of relevant ecosystem services from past studies. Table 3 summarizes the previous studies for each land cover type. Each row represents land cover types and the columns indicate types of ecosystem services. Each cell represents the number of studies for the corresponding services and cover types.

Table 3 Collected Studies for Each Ecosystem Service

(Spatial Informatics Group, Troy et al. 2009)

Category	Recreation	Aesthetic/ amenity	Other cultural	Pollination & dispersal	Habitat refugee/ biodiversity	Atmospheric regulation	Soil retention, erosion control	Water quality/ nutrient & waste regulation	Water supply/regulation	Disturbance avoidance	# of studies used for cross tab
Agriculture											
Agriculture	1(1)		5(7)	2(3)		1(1)					9(12)
Grassland/Pasture/Hayfield	2(11)		3(4)	1(1)	1(2)	2(5)	1(4)	1(2)		1(2)	13(30)
Forest											
Forest: Non-urban	9(19)		3(6)		4(5)	1(1)		1(1)			20(36)
Forest: Urban	2(7)		1(1)	1(2)		1(1)		1(1)	1(1)		8(15)
Forest: Suburban	3(8)		1(1)			1(1)		1(1)	1(1)		8(14)
Forest: Adjacent to stream	1(2)				2(6)	1(1)	1(2)	1(1)	2(3)	1(2)	10(19)
Forest: Hedgerow			1(1)	1(1)		1(1)					4(5)
Urban herbaceous											
Urban herbaceous greenspace		2(3)	1(1)								3(4)
Open water											
Open water: River	5(10)		1(2)		1(6)			1(1)	1(3)		9(22)
Open water: Urban/suburban river	1(3)	1(1)						2(2)	1(3)		5(9)
Open water: Inland lake	5(10)	1(3)	1(2)					1(1)			8(16)
Open water: Great Lake nearshore	3(6)	1(1)									4(7)
Open water: Estuary/tidal bay	3(6)	2(3)			2(3)			1(1)	1(2)		9(15)
Wetlands											
Wetlands: Non-urban, non-costal	3(4)	3(5)	2(4)		2(4)	1(1)		6(9)			18(29)
Wetlands: Urban/suburban	1(2)	2(3)				1(1)		5(6)	1(1)	2(6)	12(19)
Wetlands: Great Lakes coastal	1(2)	1(9)	1(2)			1(1)		6(8)			10(22)
Beach											
Beach: General	7(9)	3(7)								2(3)	12(19)
Beach: Near structures	6(8)	3(7)								2(3)	11(18)
Beach: Not near structures	5(7)										5(7)

Once necessary studies are collected, researchers map the outcomes using GIS. Transferred values are mapped in cells. If the land cover uses a 30M x 30M cell size, each corresponding value is mapped with the same cell size. Figure 7 is an example from an existing study utilizing the value transfer method. As can be seen, southern Ontario is mapped with corresponding ecosystem services values in a 15M x 15M cell size. The darker the color scheme, the higher the ecosystem values.

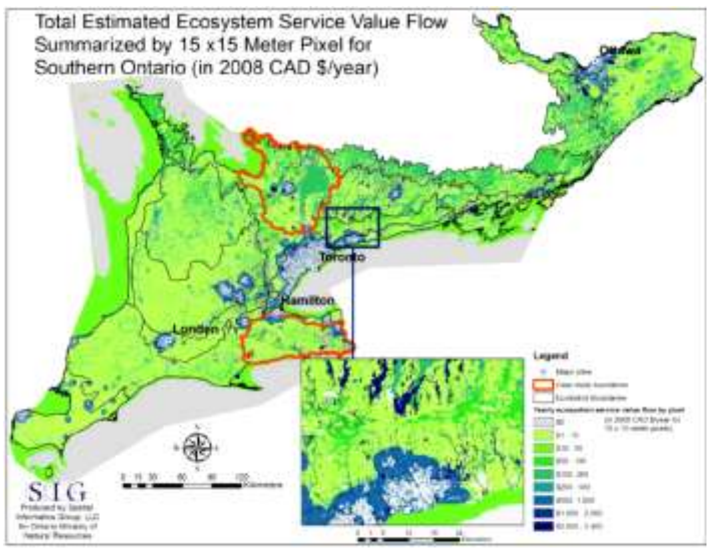


Figure 7 Total Ecosystem Service Values by Pixel
(Spatial Informatics Group, Troy et al. 2009)

In this dissertation a similar approach is adopted to calculate each route's ecosystem service consumptions. Relevant literature is collected and the existing databases such as the Environmental Valuation Reference Inventory (EVRI) or the Natural Capital Project (NCP) are actively utilized. EVRI is an online database storing all the published literature for ecosystem valuation studies. Its use is very versatile as the website not only provides the values of services, but also articulates how those values are calculated with the different types of methodologies (EVRI 2011). NCP consists of four organizations developing tools that make it easy to incorporate natural capital into decisions. There are several tools to calculate natural capital in monetary values and the organization provides links to various published research works (Natural Capital Project 2011). Using my own literature collection and existing databases like EVRI or NCP, I have estimated the ecosystem service's financial values for the study area and implemented these as environmental costs in the final route comparison stage.

3.4.4 Total Cost Comparison

For the final step, all the attributes are converted into monetary terms and summed to calculate the total costs associated with each route. Figure 8 indicates the expected attributes for each cost category. As can be seen, the construction cost deals with the direct expenditures to build the HSR (Chester and Horvath 2010; Wang and Sanders 2011). As this category relates to the direct expenditures, construction and land acquisition costs are the main attributes. This construction cost information is already in hand for the Korean HSR standard.

Operation costs include maintenance aspects (Janic 2003; Rocky Mountain Rail Authority 2010). HSR requires a few different maintenance processes and HSR-related research have already defined the attributes. In addition to maintenance costs, other operational attributes are also considered. Despite the fact that HSR consumes no fuel, it still demands electricity which should be considered a cost attribute. Further, different route lengths indicate different travel times and such distinctions should be included as a cost attribute.

Environmental costs are calculated using value transfer, and previous research suggests that there are about six ecosystem services that are valued in monetary terms. As these are expected attributes, they may change based on data availability (Kreuter, Harris et al. 2001; Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004;

Wilson, Troy et al. 2004). Using EVRI and NCP, these costs are identified and calculated with land cover satellite images.

All three attributes will be tested with different ridership levels. For example, Chester and Hovarth's 2010 article tested the effect of different ridership levels for Return-On-Investment (ROI) on the California HSR(Chester and Horvath 2010). Assuming German standard HSR vehicles would be used for the HSR system, the minimum occupancy was thus calculated as10% (120 passengers), the maximum 100% (1200 passengers), and the average 63% (761 passengers). In this dissertation, I follow these standards and test the differences in the three ridership levels.

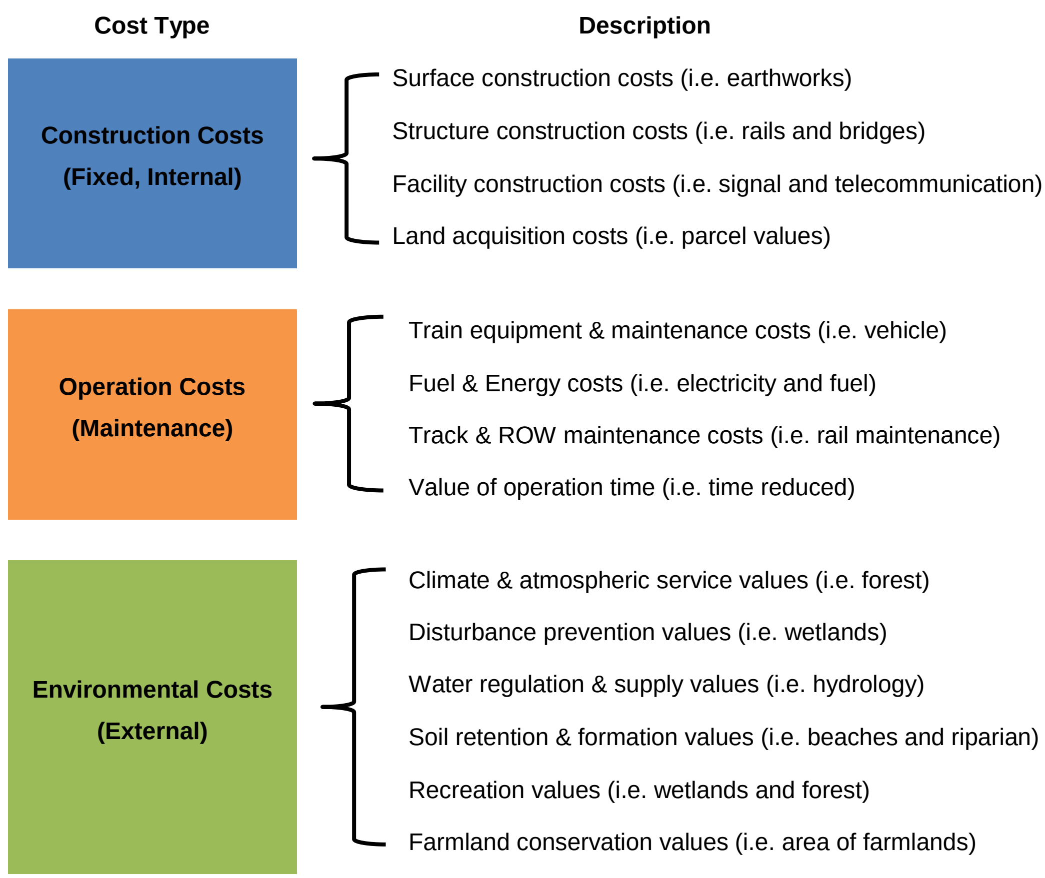


Figure 8 Attributes for Each Cost

In addition, a time measure will be added to calculate the total costs. In many cases, the U.S. implements a 30-to 50-year efficiency period (ROI period) for transportation investments with a 7% discount rate (Hayashi and Morisugi 2000; Lee 2000; Morisugi 2000; Chester and Horvath 2010). Following this convention, each HSR's total cost in this study will be calculated with a 30-to 50-year lifespan and at a 7% discount rate. Finally, as it would differ based on the number of groups generated with the CFA, I expect to have less than five routes to test total costs, ridership levels, and efficiency periods.

3.5 Data Characteristics & Sources

Datasets required in this research are spatial in nature; most of them will be collected in a geographic format. There are particular governments and institutes that provide such datasets. Some of them are open to the general public, whereas some are classified. Table 4 identifies expected datasets and their sources. In many cases, datasets are downloadable from websites, and the previously mentioned 11 variables used in TUT are collected from the same sources.

Table 4 Data Sources & Expected Datasets

Institutions		Descriptions	Expected Data
1	U.S. Census Bureau	The U.S. Census Bureau provides comprehensive information about the general population. In addition, some other types such as hydrology or road networks can also be acquired.	- Population - Road networks - Hydrology - City boundary
2	Texas Natural Resources Information System (TNRIS)	TNRIS provides a wide range of spatial datasets for Texas. Diverse datasets from TNRIS will be utilized in this research.	- Road networks - Hydrology - City boundary - Digital Elevation Models (DEM) - Floodplain - Hydrology
3	U.S. Geological Survey (USGS)	USGS provides a wide range of raster format datasets.	- Land cover - Ecosystems - DEM
4	Federal Emergency Management Agency (FEMA)	FEMA has all the information about floodplains and disasters.	- Floodplain
5	National Wetlands Inventory (NWI)	NWI handles all the wetlands information for the U.S.	- Wetlands
6	U.S. Department of Agriculture (USDA) Geospatial Data Gateway	USDA Data Gateway provides an extensive list of geospatial datasets. Many different formats of data are available.	- Land cover - Hydrology - Geology - Soils - Climate
7	Texas Park & Wildlife (TPWD)	TPWD provides vast information regarding Texas wildlife.	- Public parks - Ecoregions
8	Columbia Regional Geospatial Service Center (CRGSC)	CRGSC is a regional information center established in 2005 by the U.S. Congress. The center provides a wide range of spatial datasets at the state level.	- Hydrology - Geology - Floodplain - DEM
9	County Appraisal Districts	County Appraisal Districts provide parcel level datasets for each county.	- Parcel values - Parcels

4. ROUTE MODELING

As briefly mentioned previously, the study area is the route segment connecting the cities of Austin and Houston, Texas. The Euclidian distance between each city's centroid is approximately 236 km (147 miles). Figure 9 shows each city's centroid and the straight distance.

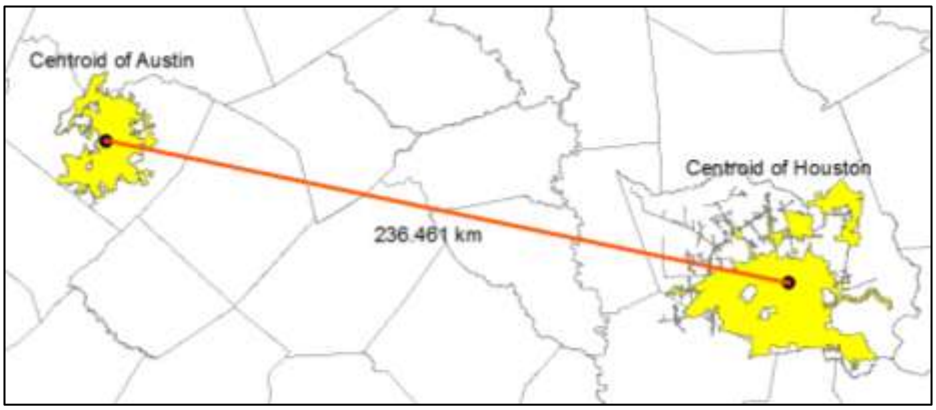


Figure 9 Straight Distances between Centroids of Austin and Houston

To properly model the route alternatives based on different input variables, it is critical to first define the study boundary. Route modeling is based on county-level datasets. Fifteen counties are within the study vicinity: Austin, Bastrop, Brazos, Burleson, Colorado, Caldwell, Fayette, Fort Bend, Grimes, Harris, Lee, Montgomery, Travis, Waller, and Washington, as illustrated in Figure 10.

The different weights assigned to input variables will likely create significant detouring from the straight-distance. By using datasets from a 15-county area, adequate margins for cases of detouring are prepared for beforehand. After route modeling is complete, only the counties through which route alternatives pass will remain displayed and be considered during the outcome interpretation process.

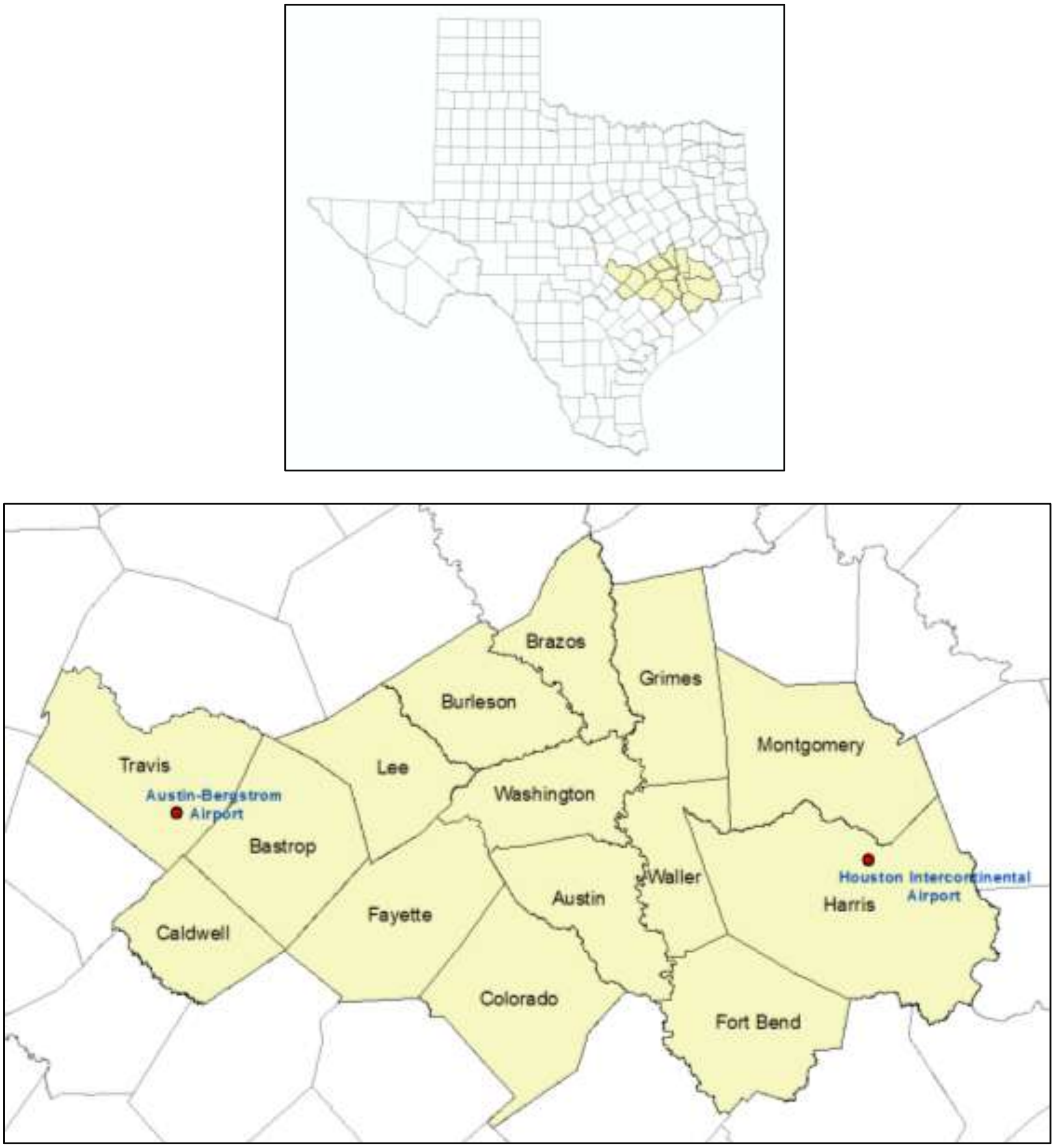


Figure 10 Study Boundaries with County Names and Two Major Airports

4.1 GIS Raster-Based Route Modeling: Spatial Decision Support System (SDSS)

GIS raster-based modeling requires five distinctive steps. First, analysts need to select input variables that are perceived as highly relevant to an HSR route. At the same time, corresponding datasets will need to be collected in geo-spatial format. The raw data can be of any types (i.e. vector or raster), but should be able to converted to a raster format for modeling in the proposed SDSS. The second step involves factor analysis. Specifically, confirmatory factor analysis (CFA) is conducted to test the validity of the factor structure. The third step is to articulate the anticipated impacts within the given groups. If a group consists of population density, land use, and property values, then the route extracted will reduce the negative impacts to these three variables. In other words, this route would minimize the probability of needing to relocate large population, to route through dense development, and to purchase higher-priced parcels. The next step concerns calculating external weights, which will result in routes that are drawn based on each group's distinct characteristic. In order to extract a route based on population density, land use, and parcel value variables, for instance, the weights associated with those variables should differ to a certain degree from the other variables. The last part of this SDSS is conducting GIS raster-based modeling that using cost surface and the shortest path functions draws each group's optimized route.

After the GIS-based modeling, route interpretation is required. Given the extracted routes, a validation process can be performed using a suitability score matrix to compare each path's suitability score. If the modeling process was done in a proper manner, the suitability scores for the prioritized variables in each path will indicate relatively low scores, meaning better suitability. Reasons for using a reversed-scale are explained in the subsequent sections. Using the same example in the above paragraph, if a route is optimized for population density, land use, and parcel value variables, the suitability score of these three variables should show lower scores than those of the other variables. The next step then is to calculate the total costs for each route. Using the previously mentioned cost parameters of construction, operation, and environmental costs, the total costs of each route are estimated and compared. Figure 11 on the next page illustrates the overall study process. The first five research steps involve the GIS raster-based modeling process, while steps 6 and 7 concern the route interpretation process.

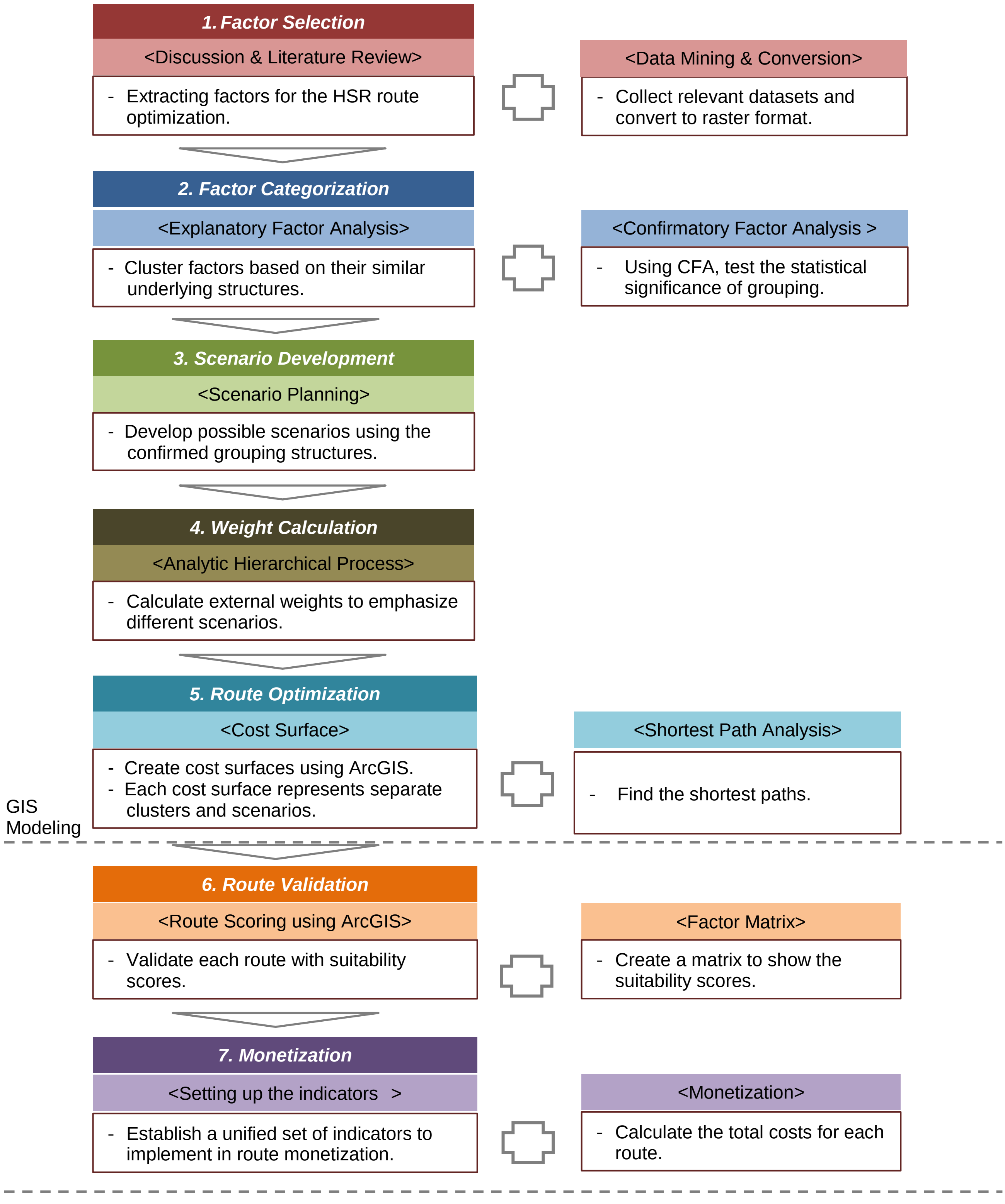


Figure 11 Overall Analysis Process

4.1.1 Input Variables

The main purpose of this first step is to articulate the variables' possible impacts on HSR routes. In addition to the inputs tested in the previous pilot studies (Kim, Wunneburger et al. 2011; Kim, Wunneburger et al. 2012), more variables are added to test the robustness of the proposed SDSS. Table 5 summarizes the selected input variables for this modeling process and they are largely into six categories.

Table 5 Selected Input Variables

No.	Category	Variables	Type
1	Engineering	Roadway Right-of-Way (type of roads)	Categorical
2		Slope (maximum grade)	Interval
3		Noise level	Interval
4	Environment	Vegetation types	Categorical
5		Productive farmlands	Numeric
6		Habitat & Wildlife management*	Categorical
7		Precipitation	Numeric
8	Natural Resources	Surface water (Hydrologic features)	Categorical
9		Aquifers	Categorical
10		Geology	Categorical
11		Soil types*	Categorical
12		Wetlands	Categorical
13		Floodplain	Categorical
14	Demographic	Population density	Numeric
15		Number of business operations (establishments)	Numeric
16	Land & Housing	Number of housing units**	Numeric
17		Land use	Categorical
18		Occupancy rate	Numeric
19		Parks, Historic sites, and Institutional facilities*	Categorical

*: Dropped after factor analysis because of an insignificant statistical result.
**: Dropped after factor analysis because of too much correlation with the Population Density variable.

This variable selection step is one of the three opportunities by which the SDSS can actively engage the public's participation. In many cases, infrastructure investment directly relates to the residents nearby. Because stakeholders' concerns can vary case by case, depending on local conditions, their inputs are necessary for more balanced investment decisions. In such cases, having stakeholders set their own goals and utilize their inputs in corridor optimization would improve overall reliability of the final outcome and reduce any unexpected negative conflicts. Two other possibilities for a more participatory GIS environment are explained subsequently.

4.1.2 Raster Conversion & Data Types

The next step is the conversion of datasets into a uniform scale. A raster format of 30m x 30m is used because the primary cell size for the digital elevation model (DEM) is in 30m x 30m. By converting all datasets into a raster format, we obtain relevant information at the pixel level. For example, if a vertical slope greater than 10 degrees is equal to a score of 2, then all the slope pixels steeper than 10 degrees are converted to a score of 2. Doing so creates a map with hundreds of different pixels, each identifiable by the reclassified scores that can be adopted and recalculated to create new information using simple mathematical approaches such as map algebra.

In this study, a 1-to-5 scale is utilized although a 1-to-9 scale has generally been recommended by the previous researchers (Saaty 1977; Bright 1992; Ramanathan 2001). Using a 5 scale increases the sensitivity of variable effects. A value of ‘5’ reflects the least desirable value for locating a transportation corridor in that place — the least suitable location. A value of ‘1’ reflects a desirable value for locating a transportation corridor — the most suitable location. The reason for using such an inverted ranking is because ArcGIS extracts the optimal route based on the least possible scores. Internal classification involves extensive input from both experts and literature reviews. Efforts were made to use supporting literature for proper classification but items without preexisting documentation in the literature actively utilized experts’ opinion.

The classification process deals with three different types of datasets: 1) numeric, 2) categorical, and 3) interval. Numeric variables such as population density or vacancy rate represent a specific number. For example, population density of 4.0 / acre indicates four residents per acre of land. Notably numeric datasets are subject to outliers, so variables should be normalized to avoid cases of extreme values dominating the dataset, while also partially correcting for data quality problems (Saisana and Trarantola 2002). There are a few different ways to standardize variables, which Freudenberg summarizes into five methods (Freudenberg 2003). Of those, "distance from the best and worst performers" was used with the following equation:

$$\text{Standardized New Score } (x) = 5 * [(x_i - x_{min}) / (x_{max} - x_{min})] \qquad (2)$$

(x_i: actual value, x_{min}: minimum value, x_{max}: maximum value)

A second type of dataset classification is categorical. This is the most widely utilized data format in this research, meaning that variables like Roads or Hydrology are uniquely identified based on their types rather than their numbers. For instance, constructing an HSR over an interstate highway will require higher costs than doing the same over a local street. Hence, building an HSR route over interstates receives a higher score than doing so over streets. Similar logic applies to Hydrology. Major streams receive higher scores than minor ones as the larger the surface water features, the more extra structures are required to build an HSR. Constructing an interstate highway on a lake not only increases costs but has a large environmental impact and should be minimized in that regard, too. Hierarchical designations are accessible through data providers. Feature Classification Codes (FCC) provides a good example for such designations (Geographic Data Technology 2011).

Last data types are interval formats. This type usually involves a second-hand analysis. For example, the Noise variable is measured in distance, and it is calculated with several other studies compounded. Noise is represented by distance rather than its decibel value or type because we want to avoid possible nuisance to nearby residents. According to Parsons Brickerhoff, noise of an HSR travels up to 360m at 360km/hr of train speed (Parsons Brinckerhoff 2010). Similar measurements are found in a study by Harris Miller & Hanson Inc. (Harris Miller & Hanson Inc. 2005). Following this, the Noise variable is classified into five categories of distance from major population centers.

4.1.3 Variable Classification

4.1.3.1 Variable #01 - Type of roads

The road dataset is reclassified using the Feature Classification Codes (FCC) provided by the U.S. Census Bureau (Geographic Data Technology 2011). The lower the network hierarchy, the more suitable the road type is for an HSR corridor. Having a rail route over an interstate highway receives a higher score (meaning it is less suitable) than doing so over a local street because highways are more costly to demolish or cross than local streets. This variable is in categorical format, and Table 6 and Figure 12 summarize the reclassification results.

Table 6 Road Variable Reclassification Standard

Feature Class Codes	Road Types	Suitability Scores
A1x	Primary Highway	5
A2x	Primary Road	
A3x	Secondary or Connecting Road	4
A4x	Local or Rural Road	3
A5x	Vehicular Trail	2
A6x	Cul-de-Sac or Roundabout	
A7x	Walkway or Alley	
Rail	Railroad	
No Data	No Road	1

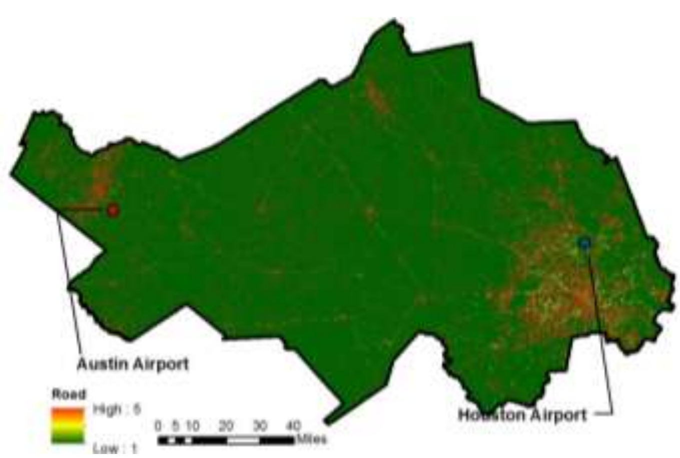


Figure 12 Reclassification of Road Variable

4.1.3.2 Variable #02 - Slope

The California High Speed Rail Authority defined vertical slope (grade) as the percentage change in elevation over every 30 meters (Parsons Brinckerhoff 2009). Following this standard, percentage change was calculated in every 30 meters using DEM. The report also details grades ranging from 0.0% to 3.50%. Grades from 0.26% to 1.25% is the most suitable to construct an HSR route, and those less than 2.5% is also considered suitable. Grades ranging from 2.51% to 3.5%, although acceptable, require extra earth works, and those less than 0.25% also necessitate extra structures to abet drainage issues. Engineering specifications allow for constructing a route on a slope above 3.5% slope, but this requires substantial costs. Although the central area of Texas is considered mostly flat, there are cases of slopes greater than 3.5% as the change is measured every 30 meter. This is in interval format, and Table 7 and Figure 13 summarize the reclassification result.

Table 7 Slope Variable Reclassification Standard

Slope Change	Descriptions	Suitability Scores
Greater than 3.51%	Significant costs and labor	5
Less than 0.25%	Acceptable with additional treatments because of possible drainage issues	4
2.51% - 3.50%	Acceptable range	3
1.26% - 2.50%	Suitable	2
0.26% - 1.25%	Most suitable	1

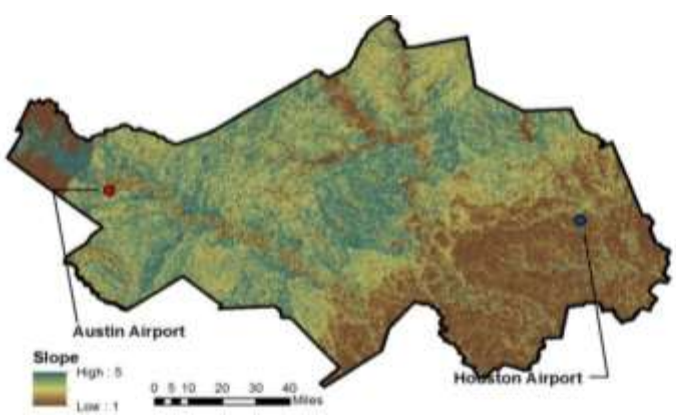


Figure 13 Reclassification of Slope Variable

4.1.3.3 Variable #03 – Noise level

Noise is calculated by distance from major population centers and is in interval format. To identify main population centers, block groups with population density higher than 4.0 persons / acre are selected (presumably one household for one acre of land), after which expected noise levels for each population center are estimated.

The California High Speed Rail Authority and a private firm Harris Miller & Hanson Inc. conducted two studies of HSR and noise. According to the studies, the noise produced by high-speed rail travels up to 1,200 feet (360 meters). The studies suggest four guidelines for screening distance (California High-Speed Rail Authority 2005; Harris Miller & Hanson Inc. 2005). Table 8 and Figure 14 summarize the result.

Table 8 Noise Variable Reclassification Standard

Distance	Descriptions	Suitability Scores
Shorter than 300ft (~ 90m)	Critical in urban settings	5
300ft – 700ft (90m – 210m)	Critical in suburban settings	4
700ft – 1,200ft (210m – 360m)	Critical in rural settings	3
Longer than 1,200ft (360m ~)	Safe distance in all settings	1

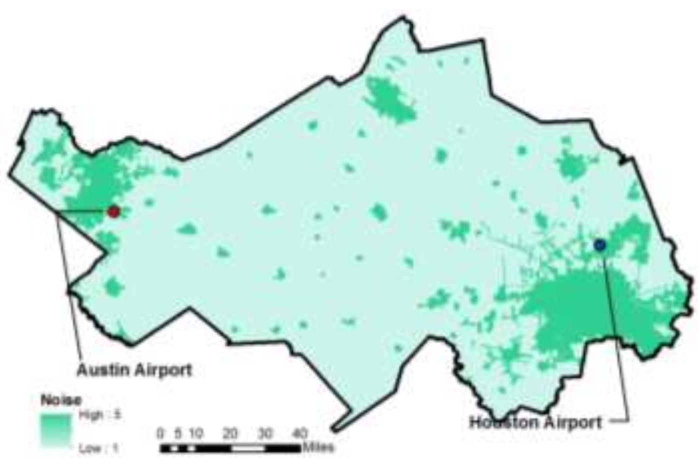


Figure 14 Reclassification of Noise Variable

4.1.3.4 Variable #04 – Vegetation type

The Vegetation dataset was acquired from the National Land Cover Institute and the Texas Parks and Wildlife Service. It categorizes vegetation as forest, shrubs, crops, pasture, grassland, and barren land. Forest indicates an area dominated by trees generally greater than 5 meters tall. Shrubs imply areas dominated by shrubs less than 5 meters. Pasture is a class of area planted for livestock grazing, while Grass represents open areas needing no significant management (The Land Cover Institute 2001; Texas Parks & Wildlife 2012). This is in categorical variable. Table 9 and Figure 15 summarize the reclassification result.

Table 9 Vegetation Variable Reclassification Standard

Types	Descriptions	Suitability Scores
Forest	Trees greater than 5 meter tall and greater than 20% of total vegetation cover	5
Shrub / Scrub	Shrubs less than 5 meter tall and greater than 20% of total vegetation cover	
Crops	Areas for the production of annual crops and greater than 20% of total vegetation	4
Pasture	Planted for livestock grazing and accounts for greater than 20% of vegetation cover	
Grassland	Areas not subject to intensive management	3
Barren Land	Vegetation accounts for less than 15% of area	2
No Vegetation	No vegetation	1

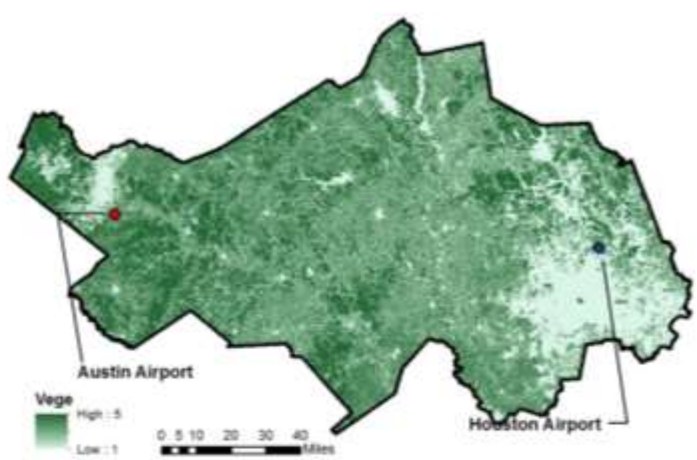


Figure 15 Reclassification of Vegetation Variable

4.1.3.5 Variable #05 – Productive farmlands

Productive farms are identified based on their number of employees. After ascertaining relevant locations, their reclassification followed a process similar to those other numeric variables: an employment density was calculated and a normalization process was performed to avoid any significant outlier effect. Adopting the equation (2), employee density was standardized into a score between 1 and 5 (Freudenberg 2003).

Table 10 shows both the standardized scores ranging from 1 to 5 and corresponding suitability scores. The higher the standard score, the less suitable is that farmland for an HSR route because the higher standard score indicates farms with higher employment, and thus more productivity. Figure 16 illustrates the result.

Table 10 Farmland Variable Reclassification Standard

Standardized Score	Descriptions	Suitability Scores
5	Highest number of employees	5
4		4
3		3
2		2
1	Least number of employees	1

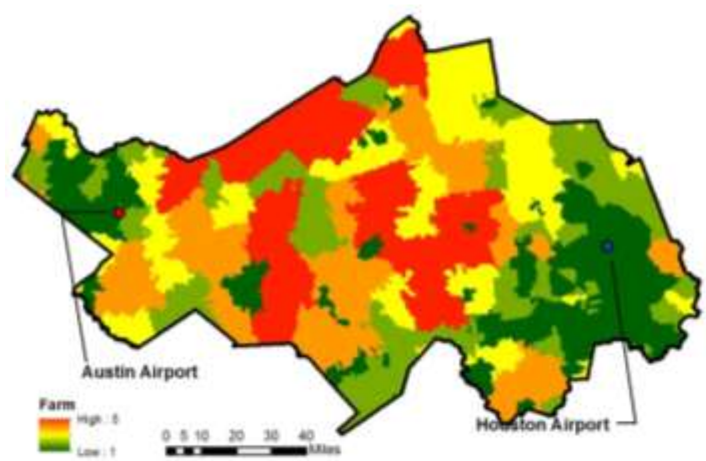


Figure 16 Reclassification of Farm Variable

4.1.3.6 Variable #06 – Critical habitat & wildlife management

There are two endangered species and one preserved habitat area inside the study boundary. The Houston Toad and Attwater Prairie Chicken are registered as critical species by the U.S. Fish and Wildlife Service (U.S. Fish & Wildlife Service 2012). The Bee Caves Preserve is also registered to preserve potential habitat for endangered species.

As interference of any kind in these features is nonnegotiable, each habitat and species should be classified as a score of 5, the least suitable for an HSR. In other words, this variable is closer to a dummy variable. Table 11 and Figure 17 summarize the reclassification result.

Table 11 Habitat Variable Reclassification Standard

Habitat / Species	Descriptions	Suitability Scores
Houston Toad	Critical specie	5
Bee Caves Preserve	Endangered species habitat and potential preserve area	5
Attwater Prairie Chicken	Endangered specie	5
No Habitat	No habitat	1

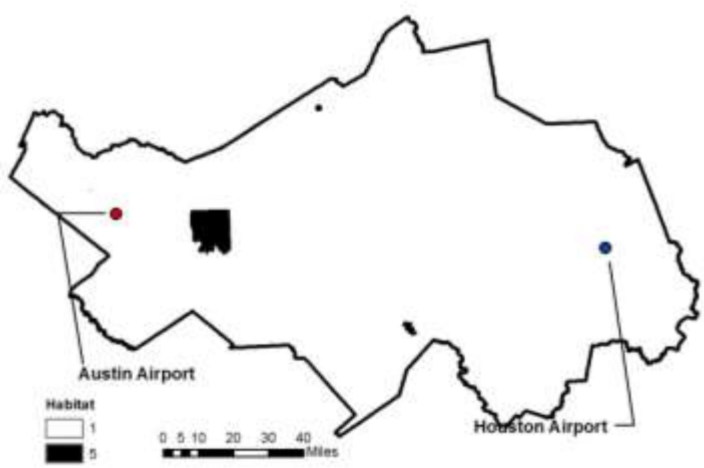


Figure 17 Reclassification of Habitat & Wildlife Variable

4.1.3.7 Variable #07 – Annual precipitation

The annual precipitation rate is intended to identify the areas highly susceptible to the risks associated with heavy rainfalls (i.e. flooding or wash outs). Within the study area, the highest average annual precipitation is 51 inches, and the lowest is 31 inches (Texas Water Development 2012).

Similar to the Farmland variable, annual precipitation is numerically formatted and needs to be standardized. Using the same equation (2), the precipitation variable is normalized with a score of 1 indicating the most suitable for an HSR and 5 as the least suitable. Table 12 and Figure 18 summarize the result.

Table 12 Precipitation Variable Reclassification Standard

Standardized Score	Descriptions	Suitability Scores
5	Highest average of annual precipitation	5
4		4
3		3
2		2
1	Lowest average of annual precipitation	1

Figure 18 Reclassification of Precipitation Variable

4.1.3.8 Variable #08 – Hydrologic features

Similar to the Road variable, Hydrology is reclassified using the FCC (Geographic Data Technology 2011). The FCC defines hydrology according to its size and function. The larger the feature, the harder an HSR is to construct because a substantial amount of extra structures will be required. Additionally, constructing an HSR over a lake has an environmental impact that should not be disregarded.

Starting from small streams to major water features such as lakes or reservoirs, the FCC provides a hierarchy of hydrology within the study vicinity. Table 13 and Figure 19 summarize the result, and this is a categorical variable.

Table 13 Hydrologic Unit Variable Reclassification Standard

Features	Descriptions	Suitability Scores
Dam	Dam structures	5
Lake	Lake or reservoirs	
Water Body	Small-sized water bodies	4
Major Streams	Large category rivers and streams	
Intermittent Streams	Medium-sized streams	3
Streams	Brooks or small-sized streams	2
No Streams	No water features	1

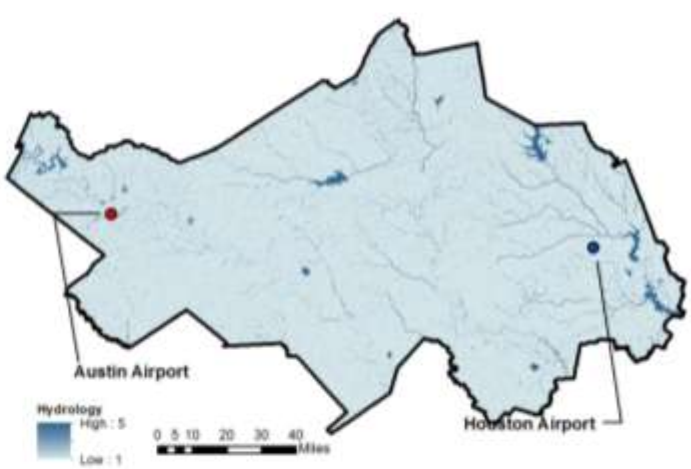


Figure 19 Reclassification of Hydrologic Units Variable

4.1.3.9 Variable #09 – Aquifers

Aquifer recharge zones affect water sources to a certain degree. This variable is selected to avoid the probability of an infrastructure facility contaminating major water sources (George, Mace et al. 2011).

Aquifers are categorized into freshwater saturated thickness. Major aquifers are rated less suitable as they are primary water sources, and their recharge thickness is much thicker than minor aquifers. Table 14 and Figure 20 summarize the reclassification system and result.

Table 14 Aquifer Variable Reclassification Standard

Name & Type		Descriptions	Suitability Scores
Major	Trinity	Freshwater saturated thickness: 1,900ft	5
	Gulf Coast	Freshwater saturated thickness: 1,000ft	
	Carrizo-Wilcox	Freshwater saturated thickness: 670ft	4
	Edwards-Trinity	Freshwater saturated thickness: 433ft	
Minor	Yegua-Jackson	Freshwater saturated thickness: 170ft	2
No Data		No aquifer areas	1

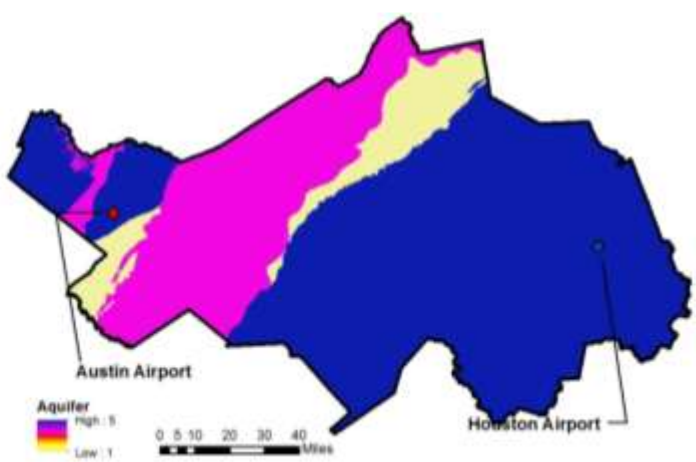


Figure 20 Reclassification of Aquifer Variable

4.1.3.10 Variable #10 – Geology

Geology relates to construction suitability and the vibration aspect in HSR operation. Using the U.S.G.S. defined geologic units in Texas (U.S. Geological Survey 2010), the study boundary is largely divided into six geologic features. Limestone is the most resistant and prevalent geology for construction, while mudstone and sandstone, although also types of sedimentary rocks, are not as hardy as limestone. Clay and sand, porous and unstable in nature, are scored the least suitable scores. Table 15 and Figure 21 summarize the reclassification result.

Table 15 Geology Variable Reclassification Standard

Geologic Units	Descriptions	Suitability Scores
Sand	-	5
Water	-	
Gravel	-	3
Mudstone	Fine grained sedimentary rock	2
Sandstone	Clastic sedimentary rock	
Limestone	More resistant than most sedimentary rocks	1

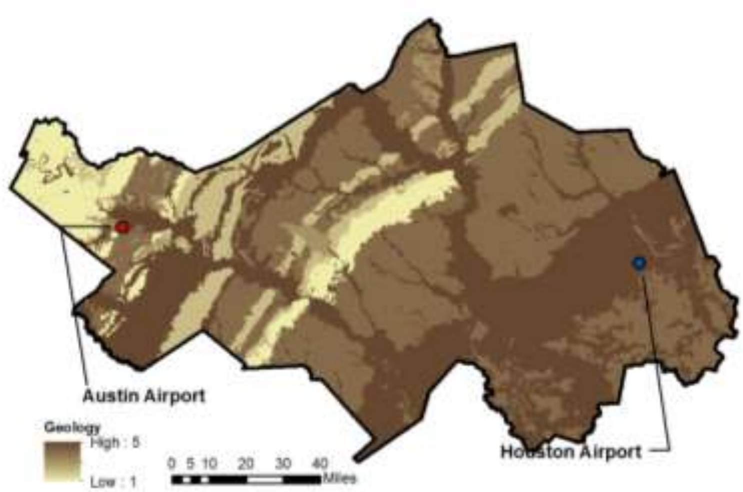


Figure 21 Reclassification of Geology Variable

4.1.3.11 Variable #11 – Soil types

Soil Type is reclassified using the Soil Survey Reports provided by the University of Missouri. The report is drawn based on several different suitability options (University of Missouri 2012).

In this study, each soil type is categorized by construction suitability for transportation infrastructure, such as local streets, ranging from Not Limited to Very Limited. Very Limited indicates soil types on which constructing a road or street is strictly limited because of structural stability and substantial costs. Table 16 and Figure 22 summarize the reclassification result

Table 16 Soil Variable Reclassification Standard

Soil Units	Descriptions	Suitability Scores
Very Limited	Very limited to construct roads and streets	5
Somewhat Limited	Somewhat limited to construct roads and streets	4
Not Limited	Not limited to construct roads and streets	1

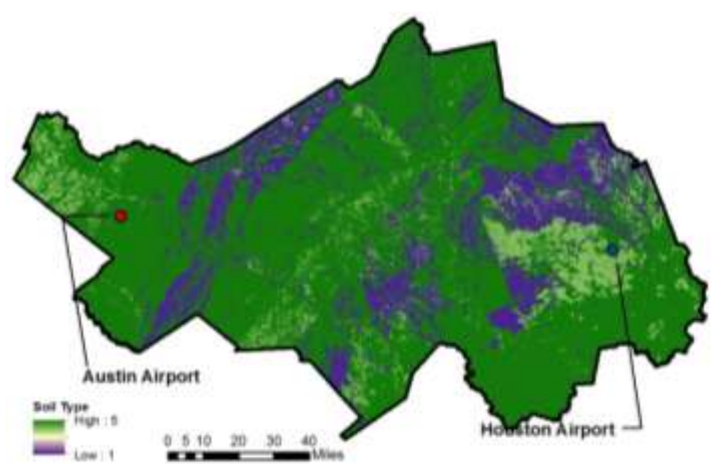


Figure 22 Reclassification of Soil Type Variable

4.1.3.12 Variable #12 – Wetlands

The Wetland variable is intended to preserve environmentally beneficial wetlands. There are two dominant types of wetlands in the study vicinity. Using the National Wetland Inventory datasets provided by the U.S. Fish & Wildlife Service (US Fish & Wildlife Service 2012), this variable is reclassified categorically based on the area's percentage of vegetation covers. Table 17 and Figure 23 summarize reclassification the result.

Table 17 Wetland Variable Reclassification Standard

Type	Descriptions	Suitability Scores
Herbaceous Wetlands	Saturated area with vegetation accounts for more than 80%	5
Woody Wetlands	Saturated area with vegetation accounts for more than 20%	4
No Data	No Wetlands	1

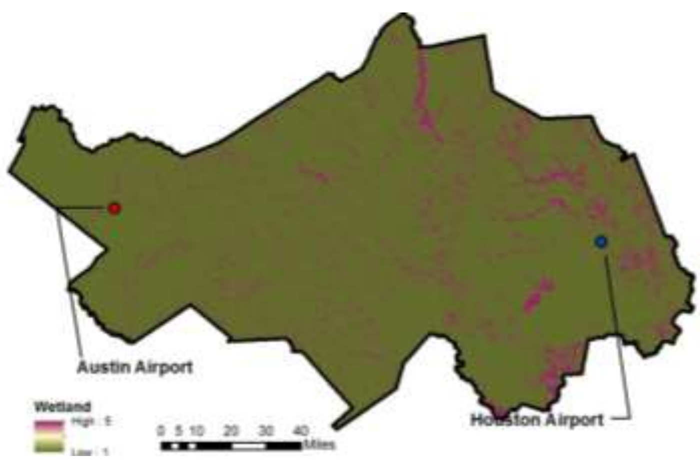


Figure 23 Reclassification of Wetland Variable

4.1.3.13 Variable #13 – Floodplain

Similar to the Precipitation variable, the Floodplain variable identifies areas with higher risks of flooding. Higher probability for flooding is dangerous to both construction and operation and should be avoided. The Federal Emergency Management Agency (FEMA) provides an annual probability of flooding for each county in the U.S. (Federal Emergency Management Agency). This is a categorical variable. Table 15 and Figure 24 summarize the result.

Table 18 Floodplain Variable Reclassification Standard

Type	Descriptions	Suitability Scores
AE	100YR floodplain with base elevation given	5
AO	100YR floodplain with average depth 1-3feet	4
X500	Areas between 100 – 500YR floodplain	3
X	500YR floodplain with less than 0.2% probability	2
No Data	No floodplain	1

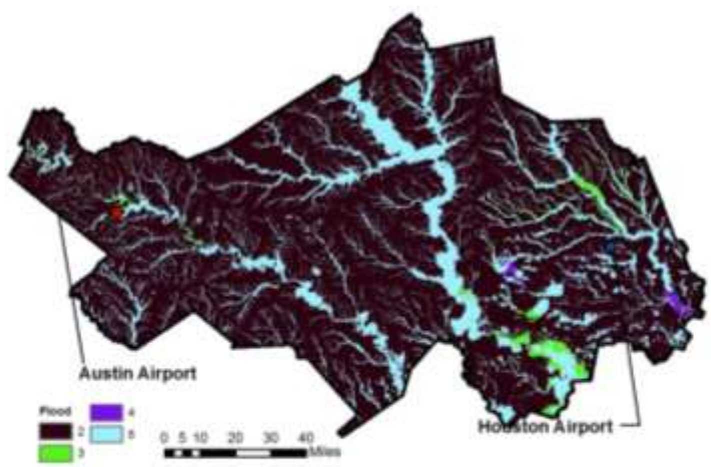


Figure 24 Reclassification of Floodplain Variable

4.1.3.14 Variable #14 – Population density

Population density is important because it indicates the scale of potential reallocation of people and goods. A higher density implies higher cost, while the relocation of more people and goods also raises the chance for conflicts. Although higher density may imply easier accessibility, decisions regarding locations of stations are not part of this modeling process due to its political nature. Thus, density will only be considered for routing purpose.

The Population Density variable is classified in numeric format and needs to be standardized with the same equation (2). In other words, a normalized value of 5 indicates the highest level of population density and least suitable for an HSR, while a value of 1 means the lowest level of population density and most suitable for an HSR. Table 19 and Figure 25 summarize the result.

Table 19 Population Variable Reclassification Standard

Standardized Score	Descriptions	Suitability Scores
5	Areas with the highest density	5
4		4
3		3
2		2
1	Areas with the lowest density	1

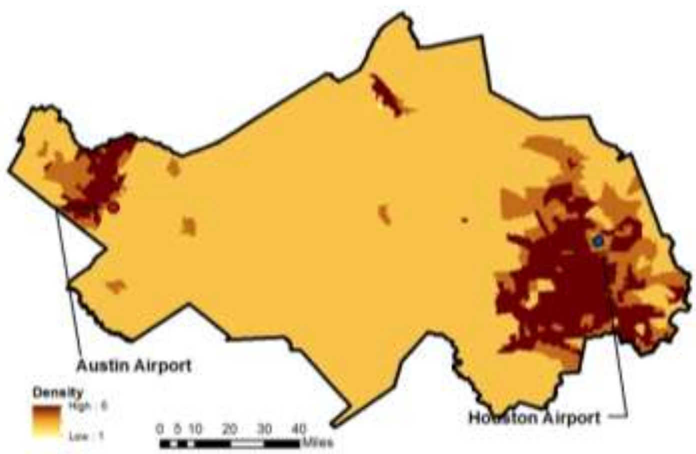


Figure 25 Reclassification of Population Density Variable

4.1.3.15 Variable #15 – Number of business operations

This variable is intended to identify areas of high job concentration. Research park or suburban-type office complexes are good examples of areas that need to be avoided for the same reason discussed in the Population Density variable. To obtain the job density, the number of business establishments in the study boundary is gathered from the U.S.

Census Bureau decennial census dataset and is in numeric format. Similar to the other numeric type variables, this variable is also normalized to avoid any effects from outliers. The lower the number of business operations, the more suitable the area for an HSR route as it reduces the probability of relocating jobs or business establishments. Table 20 and Figure 26 summarize the result.

Table 20 Job Variable Reclassification Standard

Standardized Score	Descriptions	Suitability Scores
5	Areas with the most number of jobs	5
4	↓	4
3		3
2		2
1	Areas with the least number of jobs	1

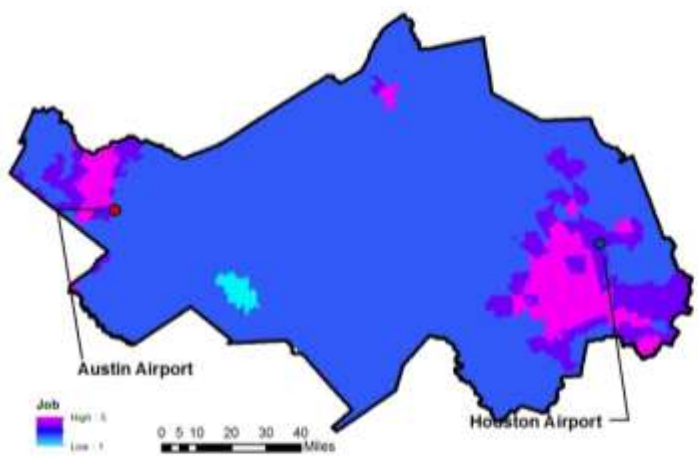


Figure 26 Reclassification of Job Density Variable

4.1.3.16 Variable #16 – Number of housing units

Similar to the Population Density and Job Density variables, the total number of housing units also measures the potential need to relocate people and goods. In this case, however, the variable is intended to avoid highly crowded housing areas. The number of housing units per acre of land is calculated as a numeric variable requiring the same standardization process. Table 21 and Figure 27 summarize the result.

However, this variable demonstrated significant correlation with the Population Density variable ($r=0.85, p < 0.01$), and accordingly was dropped from the factor analysis result. This is an anticipated result as highly populated areas usually possess more housing units compared to lower density areas.

Table 21 Housing Unit Variable Reclassification Standard

Standardized Score	Descriptions	Suitability Scores
5	Areas with the most housing units	5
4		4
3		3
2		2
1	Areas with the least housing units	1

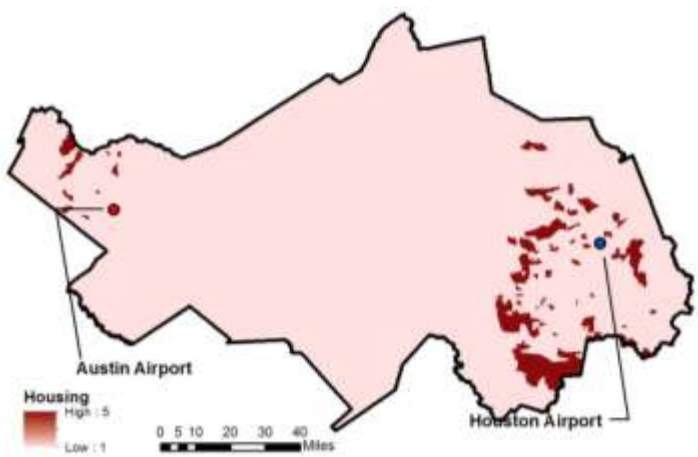


Figure 27 Reclassification of Housing Unit Variable

4.1.3.17 Variable #17 – Land use

Using the land cover imagery and designations from the U.S.G.S. (Environmental Protention Agency 2001), land use is divided into categories of development intensity.

More developed regions imply higher probability of destruction of goods and environment and should be avoided.

Areas with no impervious surface are categorized as Rural Area. Open Space implies areas of mostly vegetation areas with some constructed materials. Increasing percentages of impervious coverage lead to Low Intensity (20%-49%), Medium Intensity (50%-79%), and High Intensity (80%-100%) categories. Land Use variable is in categorical format. Table 22 and Figure 28 summarize the reclassification result.

Table 22 Land Use Variable Reclassification Standard

Land Use	Descriptions	Suitability Scores
High Intensity	Impervious surface account for 80% – 100%	5
Medium Intensity	Impervious surface account for 50% – 79%	4
Low Intensity	Impervious surface account for 20% – 49%	3
Open Space	Impervious surface account for less than 20%	2
No Development	No or very minimum constructed materials	1

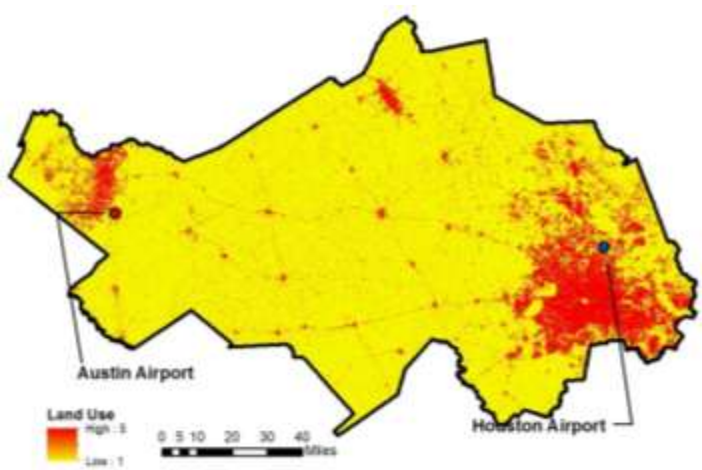


Figure 28 Reclassification of Land Use Variable

4.1.3.18 Variable #18 – Occupancy rate

Similar to the Population Density and Land Use variables, Occupancy rate is intended to locate an HSR route on vacant lands. The lower the rate of occupancy, the more suitable the area is for an HSR route as this minimizes the probability of inducing conflicts between an HSR route and people.

Obtained from the U.S. Census Bureau, an occupancy rate of 30 indicates that 30% of units in a census tract are occupied (70% of vacancy). This is a numeric variable and needs to be converted into standardized scores using the same equation (2). Table 23 and Figure 29 summarize the reclassification result. Metropolitan areas show lower suitability scores due to their higher occupancy rate.

Table 23 Occupancy Variable Reclassification Standard

Standardized Score	Descriptions	Suitability Scores
5	Areas with the highest occupancy rate	5
4	↓	4
3		3
2		2
1	Areas with the lowest occupancy rate	1

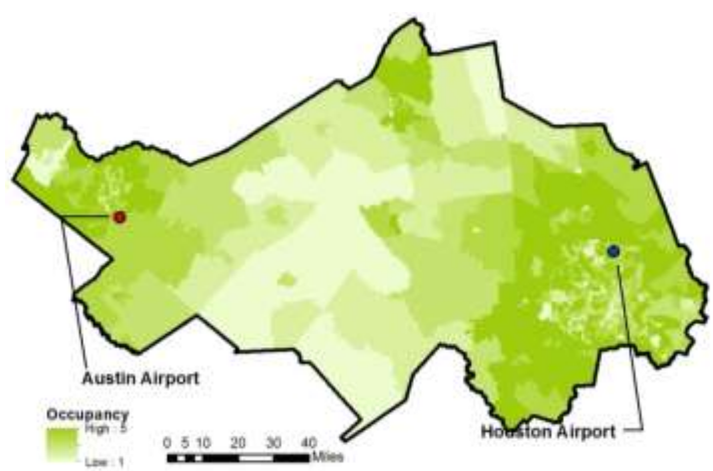


Figure 29 Reclassification of Occupancy Rate Variable

4.1.3.19 Variable #19 – Parks, historic sites, and institutional facilities

Constructing a rail route on a state park is virtually impossible considering state parks' history and sizes. Hence, it would be more reasonable to construct on a "no park" area or where locally owned, small-sized parks are located. The study area contains a few nationally registered historic sites and one federally managed park. In addition, there are parks managed by the state, counties, and municipalities as well. Golf courses and small open green spaces are also identified in order to preserve local green space. The Texas Natural Resources Information System (TNRIS) provides a list of major infrastructural facilities across the state of Texas, which this study takes into account.

Institutional facilities include military bases, airports, universities, and other government-owned facilities. Most of these facilities are fairly large and difficult to move or relocate due to a variety of reasons. Therefore, a route should minimize the possibility of going across such spots. This variable is in categorical format, and Table 24 and Figure 30 summarize the result.

Table 24 Parks and Historic Sites Variable Reclassification Standard

Types		Descriptions	Suitability Scores
Parks	National Register	National registered historic places	5
	National Park	Federal managed parks	
	State Park	State managed parks	4
	County Park	County managed parks	
	Municipal Park	Local governed parks	3
	Golf Course	Public & private golf courses	
	Open Space	Open green spaces	2
Institutional	Military Base	Military facilities	5
	Airport	Municipal and international airports	
	University	University and college facilities	4
	School	Private and public schools	3
	Research Center	Research centers	2
No Data		No facilities	1

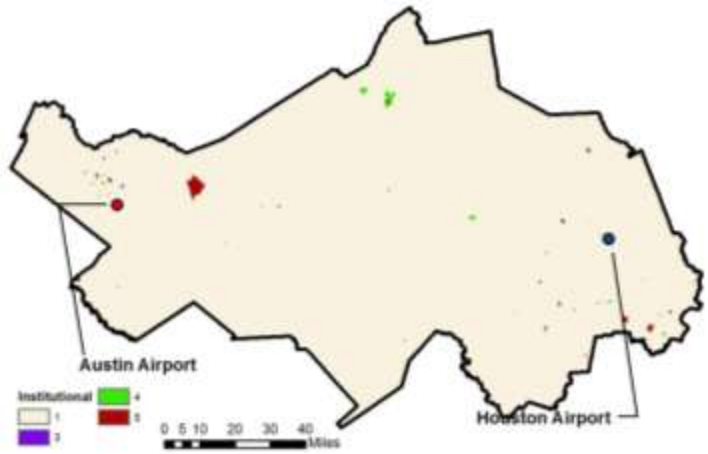


Figure 30 Reclassification of Institutional Facilities Variable

4.1.3.20 Summary

Using the relevant literature reviews and discussion with experts as reference, the above reclassification process was completed. This is the second possibility for the proposed SDSS to engage public opinions. Stakeholders are able to set their own objectives with help from experts by receiving professional advice on each variable's theoretical classification. Considering the various inputs from public participants and providing a collaborative decision-making environment reflects a small but growing trend in SDSS.

4.1.4 Confirmatory Factor Analysis

To perform a confirmatory factor analysis (CFA), a factor structure should be designed first. Figure 12 illustrates the possible underlying structure and its associated variables based on variable classification and relevant literature reviews.

The Population Density, Occupancy Rate, and Job Density variables all pertain to socio-demographic patterns in the study boundary, and Land Use, Noise, and Road Network are good proxies to indicate the current status of the built environment. Aquifer, Geology, and Precipitation relate to ground resources to a certain degree, and Hydrologic Units, Wetlands, and Floodplain are good indices for water resources. Finally, the Productive

Farms, Vegetation, and Slope variables are adequate measures to show the green space. As can be seen, two factors relate to man-made settings, whereas the remaining three illustrate environment and ecological resources.

Using a sample with 7,990 observations, the CFA result indicates an adequate fit of the proposed model in Figure 31, χ^2 (80, N=7,990) = 5,389, $p < 0.00$. In addition, the Root Mean Square Error of Approximation (RMSEA) is 0.0927 with the confidence interval between 0.0906 and 0.0947. This result implies an adequate fit as the conventional social science research indicates an RMSEA below 0.1 as adequate (Brown 2006; Schreiber, Stage et al. 2006).

Another fit index the Standardized Root Mean Square Residual (SRMR) is calculated as 0.0691, also implying a good fit as the threshold for SRMR is generally under 0.08 (DeCoster 1998; Brown 2006; Schreiber, Stage et al. 2006). Finally, the Goodness of Fit Index (GFI), here 0.915, and Adjusted GFI (AGFI), here 0.872, also indicate that the model fit is adequate as the general social science research recommends a threshold less than 0.95 for both GFI and AGFI measures (Brown 2006; Schreiber, Stage et al. 2006).

CFA was done in eight different times to test the robustness of the model, and all outcomes implied a similar result. The only difference between the test results was the degree of factor loadings. Although some tests showed slightly higher factor loadings, the differences can be regarded as minimal as the sensitivity is less than a 5% range.

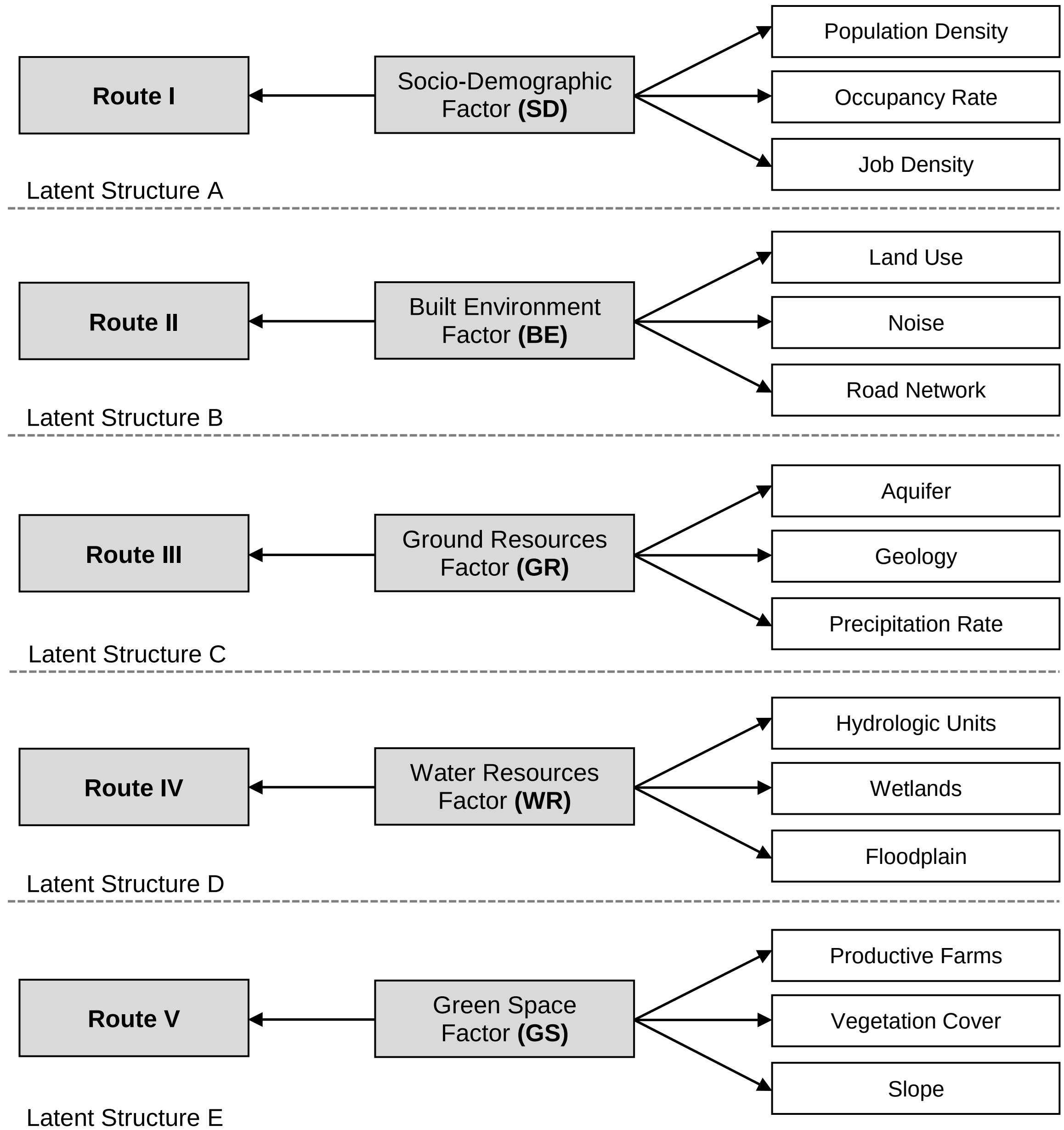


Figure 31 Latent Variable Structures

Table 25 gives the factor loading result of each factor. As can be seen, all loading values came out to be greater than 0.3 except the Vegetation variable. Although the Vegetation variable shows relatively lower loading values, this model illustrates an adequate fit based on the goodness of fit indices. Therefore, the result will be used in the inputs for the routing process. For the complete CFA result, please refer to Appendix A.

Table 25 CFA Factor Loading Completely Standardized Solution

	SD	BE	GR	WR	GS
Occupancy	0.448				
Pop. Density	0.834				
Job Density	0.925				
Road		0.418			
Land Use		0.673			
Noise		0.673			
Aquifer			0.383		
Geology			0.384		
Precipitation			1.040		
Hydrology				0.313	
Wetland				0.653	
Floodplain				0.446	
Slope					0.246
Farmlands					0.405
Vegetation					0.642

4.1.5 Possible Development Scenarios

From the CFA result, five possible development scenarios are drawn. Table 26 shows each variable's corresponding factors. As can be seen, implementing the first factor, Socio-Demographic, results in an HSR route that avoids major population centers, highly occupied blocks, and job-concentrated centers. The second factor, Built-Environment, enables the route to detour around highly developed areas, reducing the probability of crossing major roads, and minimizing negative noise effects from the HSR. The Ground-Resources factor is intended to preserve major aquifers, to find suitable geology types, and to evade higher precipitation regions. The fourth factor, Water Resources, is designed to effectively preserve water resources so its implementation reduces the probability of the route crossing major streams, environmentally beneficial wetlands, or areas at high risk to floods. The final factor, Green Space, aids in preserving green infrastructure through minimizing a route's presence on productive farmlands, finding the most suitable grades for HSR construction, and preserving natural vegetation covers.

Each of the five groups' factors in different priorities and the resulting HSR routes will vary accordingly. Such is how this modeling process improves upon the limitations identified in current SDSS practice. By scientifically grouping the input variables and suggesting possible development scenarios based on each group's underlying characteristics, the limitations that stem from the current lack of objective and scientific methods for categorizing variables are mitigated to a certain degree.

Table 26 Possible Development Scenarios

Factors	Variables
Socio-Demographic (SD)	Population Density / Occupancy Rate / Job Density
Built-Environment (BE)	Road Network / Land Use / Noise
Ground-Resources (GR)	Aquifer / Geology / Precipitation Rate
Water-Resources (WR)	Hydrologic Units / Wetlands /Floodplain
Green Space (GS)	Slope / Farmlands / Vegetation

4.1.6 Scenario Weighting

In order to differentiate each group's effect on the final route, an external weighting process is required. While there are many ways to perform the weighting process, one of the most commonly adopted methods is the Analytic Hierarchical Process (AHP), a structured technique for organizing and analyzing complex decisions. Based on mathematics and psychology, AHP was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then (Saaty 1990). Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions (Ramanathan 2001).

Using AHP with the aforementioned development scenarios, it is possible to calculate weights with simple mathematical steps. Table 27 shows the way to calculate external weights that emphasizes Factor 1 (SD), while every other factor is treated equal. The first step is to identify the relative importance between the factors, allowing the effect of Factor 1 to be emphasized by giving it a weight of 5 and a weight of 1 is allocated to all the other factors.

After that, we obtain the column values by dividing each relative importance score with the sum, (e.g., 1.00 / 1.80 = 0.56). The values are summed together and then averaged ([0.56+0.56+0.56+0.56+0.56] / 5=0.56). The Score column indicates the weights for each preferred scenario. Although the preferred factor will differ based on scenarios, the weight stays the same. Hence, the weight will be used in the same manner across the scenarios (0.56 for the emphasized factor and 0.11 for the rest). In doing so, we will be able to have a suitability surface with more weight on the target group and less weight on the others.

Table 27 External Weights with AHP for Factor 1

	SD	BE	GR	WR	GS	SUM
SD	**1.00**	5.00	5.00	5.00	5.00	21.00
BE	0.20	1.00	1.00	1.00	1.00	4.20
GR	0.20	1.00	1.00	1.00	1.00	4.20
WR	0.20	1.00	1.00	1.00	1.00	4.20
GS	0.20	1.00	1.00	1.00	1.00	4.20
SUM	**1.80**	9.00	9.00	9.00	9.00	37.80

	SD	BE	GR	WR	GS	Score	%
SD	**0.56**	0.56	0.56	0.56	0.56	**0.56**	55.56%
BE	0.11	0.11	0.11	0.11	0.11	**0.11**	11.11%
GR	0.11	0.11	0.11	0.11	0.11	**0.11**	11.11%
WR	0.11	0.11	0.11	0.11	0.11	**0.11**	11.11%
GS	0.11	0.11	0.11	0.11	0.11	**0.11**	11.11%
SUM	1.00	1.00	1.00	1.00	1.00	**1.00**	100.00%

Using the AHP result, each preferred scenario could be written as below.

$$\text{Suitability Surface for a Preferred Scenario } k = \sum_k \boldsymbol{w_k} \cdot \boldsymbol{x_k} + \sum \boldsymbol{w} \cdot \boldsymbol{x} \qquad (1)$$

Where w_k: external weight for the variables in the preferred Factor k

x_k: value of grids in the Factor k

w: external weight for the variables in the other factors

x: value of grids in the other factors

This weighting process is the last possibility during which this proposed SDSS can engage public participation. As can be seen, possible route scenarios are drawn with the CFA result, and experts can articulate distinctions of each development scenario. In this case, relevant stakeholders are able to draw up their preferred scenario by setting the weights with a method such as AHP.

4.1.7 Route Optimization

Up to this point, three steps have taken. First, data sets were prepared. After that, a confirmatory factor analysis was performed. Using the CFA result, five scenarios were drawn and weights were calculated to emphasize the target factors. Based on these three steps, GIS modeling can be performed. GIS modeling, especially raster-based modeling for locating an optimal route involves two distinct steps. First, users need to create a cost surface from the calculated factor weights, and then a shortest path analysis is performed on a cell-by-cell basis.

4.1.7.1 Cost surface

By using the equation (1), cost surfaces for each scenario are generated. For example, if we decide to create a cost surface for Scenario 1, then we multiply the Population Density, Occupancy Rate, and Job Density variables by 0.56 and the rest by 0.11. The resulting cost surface is in a raster format with each pixel indicating a suitability score based on the established scenarios. Each scenario contains a different set of variables, and the summation of variables produces different suitability scores as well. Figure 32 illustrates the visual diagram of this process.

Factor 5 (GS)		(Farmlands) * 0.11
		(Vegetation) * 0.11
	+	(Slope) * 0.11
Factor 4 (WR)		(Floodplain) * 0.11
		(Hydrology) * 0.11
	+	(Wetlands) * 0.11
Factor 3 (GR)		(Precipitation) * 0.11
		(Geology) * 0.11
	+	(Aquifers) * 0.11
Factor 2 (BE)		(Roads) * 0.11
		(Noise) * 0.11
	+	(Land Use) * 0.11
Factor 1 (SD)		(Job Density) * **0.56**
		(Occupancy Rate) * **0.56**
	+	(Pop. Density) * **0.56**

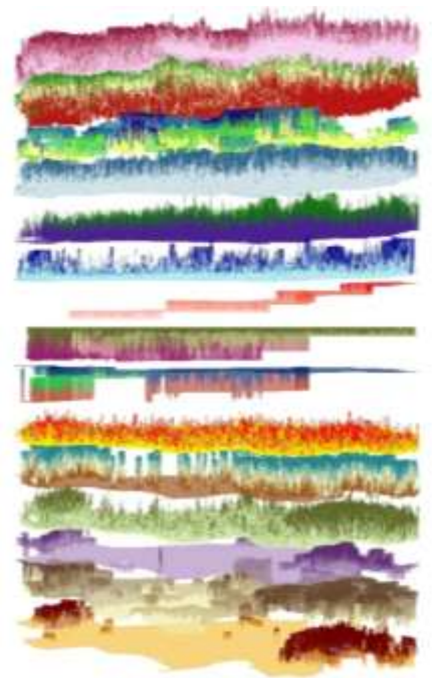


Figure 32 Visual Illustration of Raster Calculation Prioritizing the Factor 1

A cost surface needs to be calculated for each scenario. Because placing emphasis on different factors derives different cost surfaces and thus different routes, creating cost surfaces based on the preferred scenario is one of the most critical steps in this entire modeling process.

Figures 33(a) through 33(e) show the cost surface for each scenario. As the preferred group changes, the suitability score varies as well. The cost surface is also in raster format. Therefore, each pixel contains the final suitability score based on the established scenarios and the relationships between the variables. With these cost surfaces, the shortest path analysis can be conducted, and the expected HSR routes are extracted accordingly.

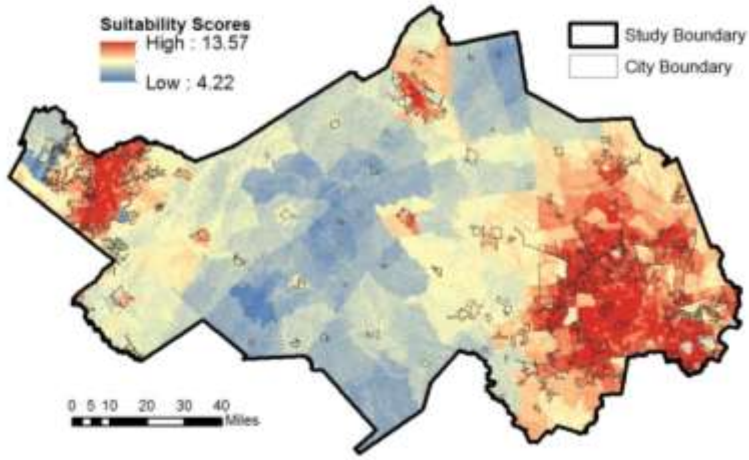


Figure 33(a) Suitability Surface for Factor 1

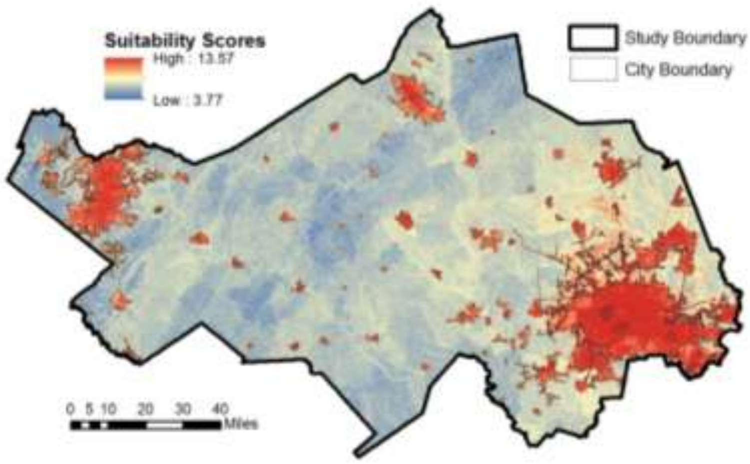


Figure 33(b) Suitability Surface for Factor 2

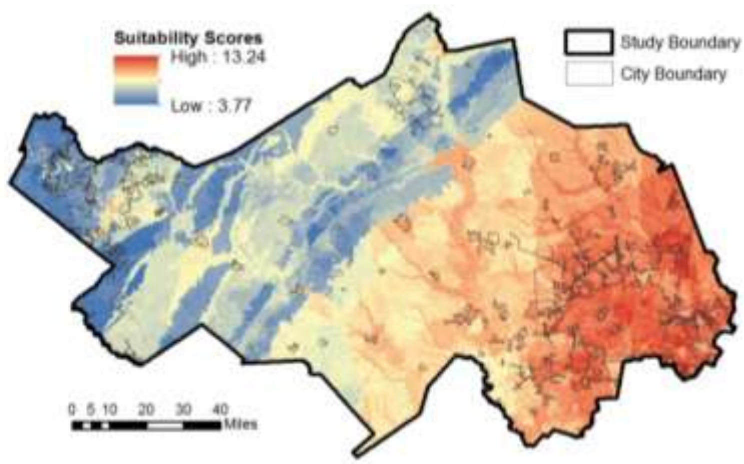


Figure 33(c) Suitability Surface for Factor 3

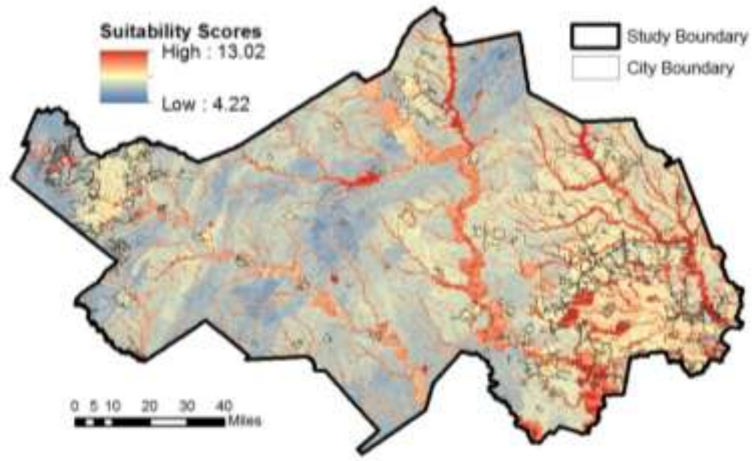


Figure 33(d) Suitability Surface for Factor 4

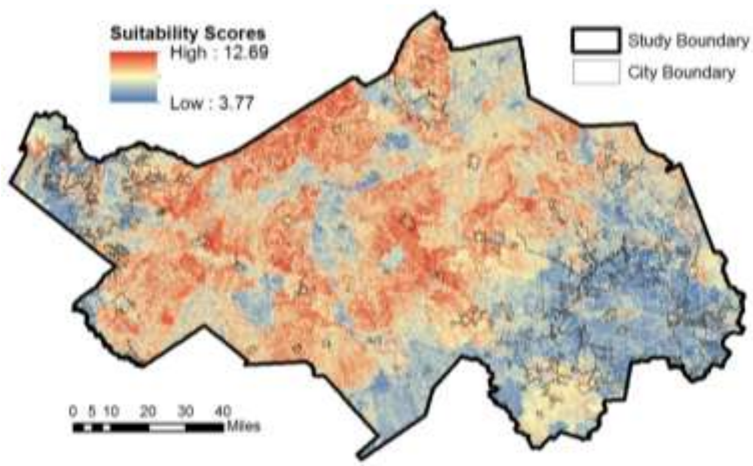


Figure 33(e) Suitability Surface for Factor 5

4.1.7.2 Shortest path

The shortest path analysis identifies the pixels with the least possible scores that can connect the two points. This is the reason why a reversed scale is used. By assigning higher scores to the preferred scenario, the shortest path analysis produces a route which avoids confronting the variables in the preferred group. For research convenience, the departure and destination points were set to the two cities' major airports. Station location involves a different set of decision-making procedures and requires a separate in-depth study. For this reason, making decisions as to the location of stations is not part of this study. I used the cities' two main airports as international airports, increasingly linked to HSR route planning in metropolitan areas worldwide. Whether the HSR route eventually begins or ends at one or both of these airports or at a different geographic location, the route modeling process does not change, and the output would vary accordingly.

ArcGIS shortest path analysis locates the pixels with the least possible scores between two designated points. After inputting up the locations of origin and destination points, the collective functions that going into a shortest path analysis seeks out the lowest scores adjacent to each proceeding pixel. The least possible scores are constantly identified and connected until the path reaches its final destination.

Figures 34(a) through 34(f) shows the optimal HSR route for each scenario, based on a shortest path analysis. Scenarios 1 and 5 produced the most unique paths, while the remaining paths resulting from Scenarios 2 to 4 are relatively similar in their shapes. Path 1 minimized passing through major population centers. Other than areas immediately surrounding the starting and ending points, most highly populated areas remain unaffected by the HSR route. Path 2 is close to being a straight line. It avoids major population centers to reduce noise effect and minimizes crossing highways. Paths 3 and 4 are quite similarly shaped because the major water and ground resources, their scenarios were intended to avoid, are concentrated on the east side of the study area and do not affect much of the route optimization. Route 5 seems to be the most distinctly shaped as it attempts to detour widely toward the southeast part of the study area. Figure 34(f) shows all routes combined onto one map.

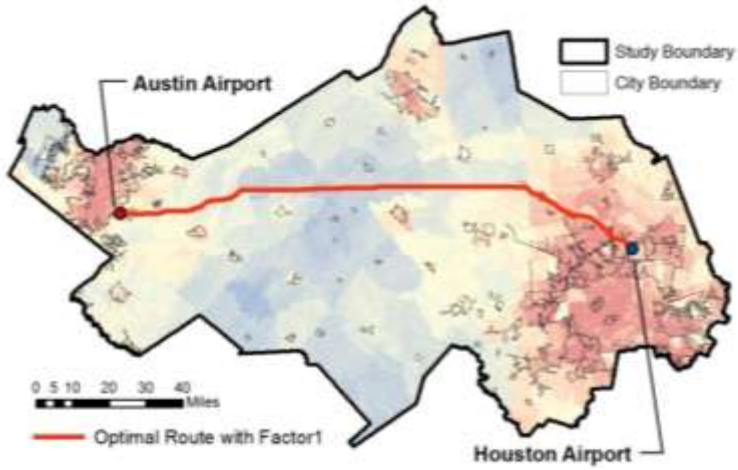


Figure 34(a) Optimal HSR Route with Prioritizing Factor 1

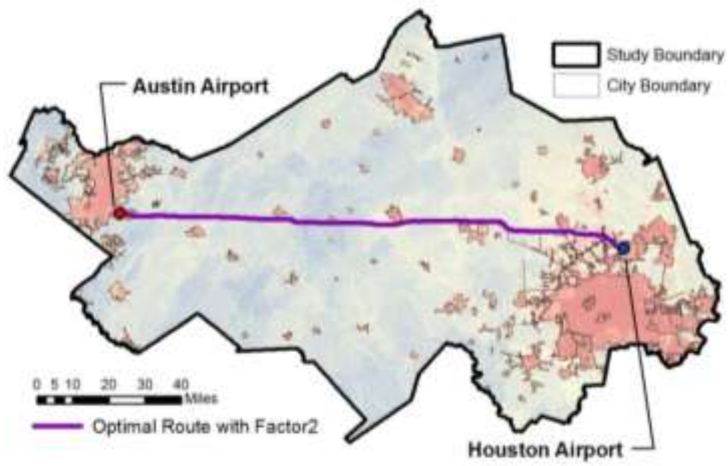


Figure 34(b) Optimal HSR Route with Prioritizing Factor 2

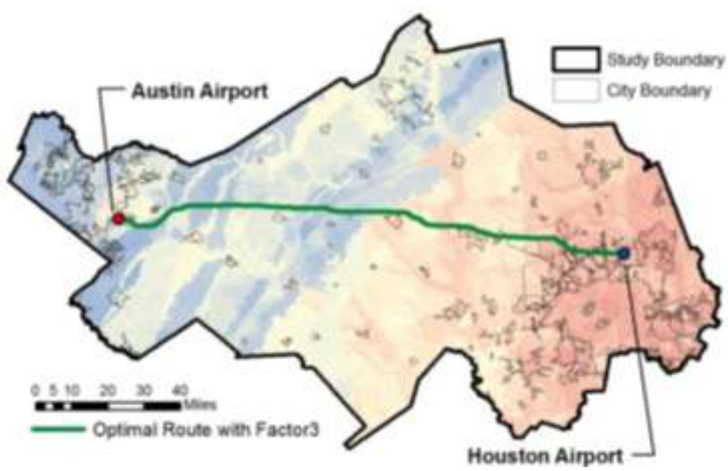


Figure 34(c) Optimal HSR Route with Prioritizing Factor 3

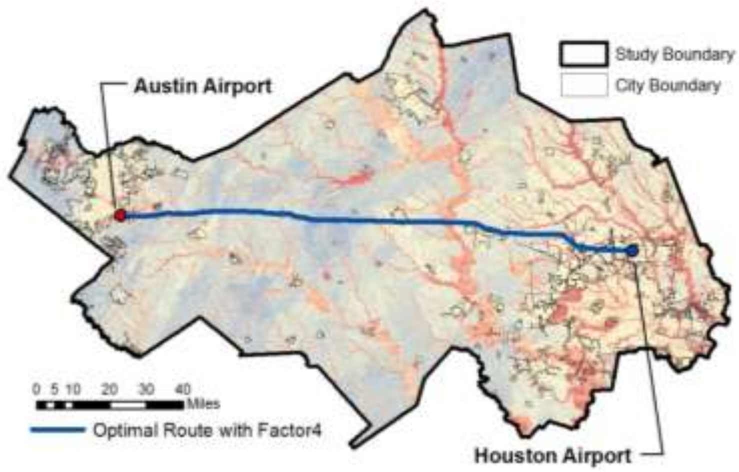


Figure 34(d) Optimal HSR Route with Prioritizing Factor 4

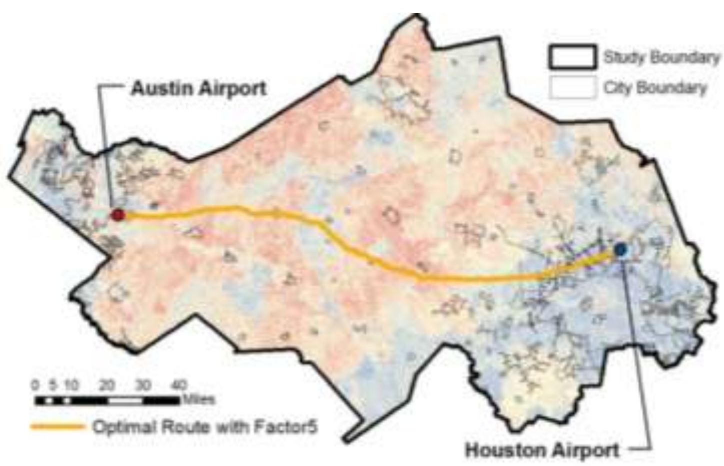


Figure 34(e) Optimal HSR Route with Prioritizing Factor 5

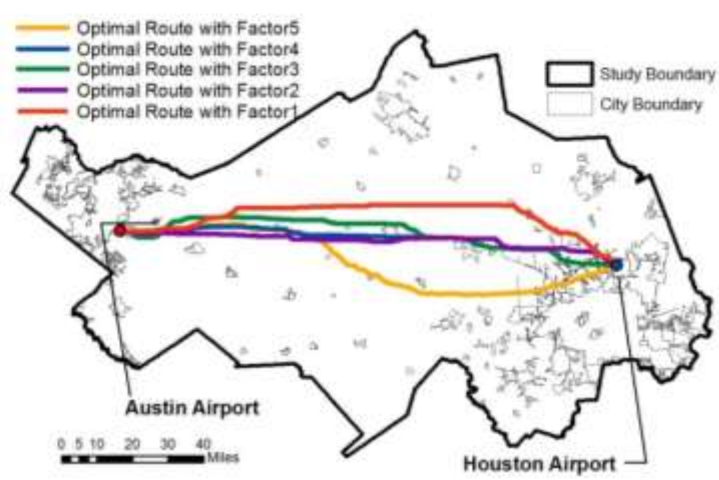


Figure 34(f) All Optimal HSR Routes Combined

4.1.7.3 Summary

As the scholars have described (Uran and Janssen 2003; Arampatzis, Kiranoudis et al. 2004; Hill, Braaten et al. 2005), one of the most significant limitations in SDSS implementation is in its inconsistent and illogical weighting system. Variable grouping and a scenario planning process have been suggested as possible remedies (Bright 1992; Hill, Braaten et al. 2005; Malczewski 2006). Such remedies, however, still possess shortcomings as they mostly are still based on users' biases, paradigms, goals, and prejudices. No scientific or statistical methods have been implemented to group the inputs when creating possible scenarios.

To overcome such limitations, a CFA was implemented as part of the proposed SDSS process. CFA offered a more logical and scientific procedure for grouping input variables with statistical significance. CFA made it possible to reduce 15 variables into five factors. Using the results, advantages and disadvantages of each possible scenario are articulated. Each group possessed its own distinctions and provided different types of benefits. The other advantage of having groups instead of a large number of inputs is increased sensitivity. As the number of items for external weights reduces, the effects of weights on the final outcome increase. Instead of using a large pool of weights for many input variables, utilizing lesser numbers of groups increases the sensitivity of weight effect. In this case, the subjective and indistinctive nature of weights on inputs becomes more sensitive to the overall decision-making environment.

Because the geographic area under this study is so large, small changes in a route could make substantial difference in cost, travel time, and other aspects of HSR implementation. Therefore, it is important to scrutinize each route and compare its implications in detail. Suitability scores of each route and anticipated costs would be appropriate indicators when comparing the route options. As mentioned previously, environmental costs will also be calculated as an opportunity cost.

5. ROUTE INTERPRETATION

Although all the routes are relatively similar in shape, they imply different associated benefits and costs because the study boundary is large. In this sense, investigating each route's precise differences in strategic attributes is a necessary part of outcome interpretation. In this section, each route will be compared on four aspects: 1) suitability scores; 2) construction costs; 3) operation costs; and 4) environmental costs.

5.1 Suitability Scores

The California High-Speed Rail Authority's study of HSR defined the ROW needed for one lane of HSR as 30 meters wide (Parsons Brinckerhoff 2004). For this study, we take into account the ROW required for two lanes, or 60 meters of width. After defining 60 meters of space around each route, suitability scores for each corridor are extracted.

Table 28 summarizes the results. The highest and lowest results are listed in bold. As can be seen, Route 1 shows the lowest suitability scores in the grand total, whereas Route 3 results in the highest. The score ranges from 1,306,809 to 1,352,802 and the suitability scores for Routes 4 and 5 imply similar records. Looking at the record in detailed, it is evident that each path ranked the least suitable in its prioritized variables. This is a reasonable output as the initial intention for giving more weight to the preferred scenario is to purposely avoid and detour around those attributes of the variables in each scenario. Path 1 scored the lowest in suitability for Population Density, Job Density, and Occupancy Rate variables, all of which represent the Socio-Demographic Factor. Path 2 scored the least suitable in Road Network, Noise, and Land Use variables (Factor 2), and Path 3 indicates the lowest suitability scores for Factor 3, the Ground Resources variables (Aquifer, Geology, and Precipitation Rate). Path 4, designed to avoid variables in the Factor 4, Water Resources, accordingly demonstrates the lowest suitability in Hydrology, Floodplain, and Wetland variables. Finally, Path 5 scored the least suitable in Factor 5's Slope, Vegetation, and Productive Farm variables.

Table 28 Suitability Matrix

Factor	Variable	Reclassification Score & Description	PATH01			PATH02			PATH03			PATH04			PATH05		
			Pixel Count	Area (m2)	**Suitability Score**	Pixel Count	Area (m2)	**Suitability Score**	Pixel Count	Area (m2)	**Suitability Score**	Pixel Count	Area (m2)	**Suitability Score**	Pixel Count	Area (m2)	**Suitability Score**
Factor 1 (SD)	Population Density	1 Density less than 17 / acre	367	330,300	367	380	342,000	380	365	328,500	365	365	328,500	365	381	342,900	381
		2 17 < Density < 35 / acre	32,278	29,050,200	64,556	32,430	29,187,000	64,860	32,115	28,903,500	64,230	31,413	28,271,700	62,826	31,634	28,470,600	63,268
		3 35 < Density < 50 / acre	3,636	3,272,400	10,908	2,114	1,902,600	6,342	1,357	1,221,300	4,071	2,062	1,855,800	6,186	1,324	1,191,600	3,972
		4 50 < Density < 56 / acre	542	487,800	2,168	1,995	1,795,500	7,980	3,074	2,766,600	12,296	3,055	2,749,500	12,220	1,291	1,161,900	5,164
		5 Density greater than 56 / acre	710	639,000	3,550	645	580,500	3,225	622	559,800	3,110	638	574,200	3,190	3,001	2,700,900	15,005
		Sum			**81,549**			**82,787**			**84,072**			**84,787**			**87,790**
	Job Density	1 Density less than 1.2 / acre	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		2 1.2 < Density < 2.1 / acre	34,211	30,789,900	68,422	32,973	29,675,700	65,946	33,494	30,144,600	66,988	33,494	30,144,600	66,988	32,170	28,953,000	64,340
		3 2.1 < Density < 3.5 / acre	3,322	2,989,800	9,966	3,231	2,907,900	9,693	1,372	1,234,800	4,116	1,373	1,235,700	4,119	1,010	909,000	3,030
		4 3.5 < Density < 4.3 / acre	-	-	-	1,360	1,224,000	5,440	1,116	1,004,400	4,464	1,066	959,400	4,264	4,172	3,754,800	16,688
		5 Density greater than 4.3 / acre	-	-	-	-	-	-	1,551	1,395,900	7,755	1,600	1,440,000	8,000	279	251,100	1,395
		Sum			**78,388**			**81,079**			**83,323**			**83,371**			**85,453**
	Occupancy Rate	1 Occupancy rate less than 0.1	14,059	12,653,100	14,059	5,964	5,367,600	5,964	5,886	5,297,400	5,886	6,290	5,661,000	6,290	8,655	7,789,500	8,655
		2 0.1 < Rate < 0.5	7,451	6,705,900	14,902	4,922	4,429,800	9,844	6,762	6,085,800	13,524	6,013	5,411,700	12,026	3,390	3,051,000	6,780
		3 0.5 < Rate < 0.8	7,705	6,934,500	23,115	9,847	8,862,300	29,541	11,466	10,319,400	34,398	11,908	10,717,200	35,724	15,308	13,777,200	45,924
		4 0.8 < Rate < 0.9	4,935	4,441,500	19,740	9,905	8,914,500	39,620	8,907	8,016,300	35,628	8,098	7,288,200	32,392	5,065	4,558,500	20,260
		5 Occupancy rate greater than 0.9	3,383	3,044,700	16,915	6,926	6,233,400	34,630	4,512	4,060,800	22,560	5,224	4,701,600	26,120	5,213	4,691,700	26,065
		Sum			**88,731**			**119,599**			**111,996**			**112,552**			**107,684**
		Sub-Total			**248,668**			**283,465**			**279,391**			**280,710**			**280,927**
Factor 2 (BE)	Noise	1 Longer than 360m	34,758	31,282,200	34,758	35,995	32,395,500	35,995	33,658	30,292,200	33,658	31,085	27,976,500	31,085	32,820	29,538,000	32,820
		3 210 - 360m	543	488,700	1,629	470	423,000	1,410	909	818,100	2,727	1,255	1,129,500	3,765	784	705,600	2,352
		4 90 - 210m	322	289,800	1,288	125	112,500	500	450	405,000	1,800	842	757,800	3,368	744	669,600	2,976
		5 Less than 90m	1,910	1,719,000	9,550	974	876,600	4,870	2,516	2,264,400	12,580	4,351	3,915,900	21,755	3,283	2,954,700	16,415
		Sum			**47,225**			**42,775**			**50,765**			**59,973**			**54,563**
	Land Use	1 No use	31,555	28,399,500	31,555	33,896	30,506,400	33,896	30,774	27,696,600	30,774	28,774	25,896,600	28,774	24,377	21,939,300	24,377
		2 Open space	3,472	3,124,800	6,944	2,458	2,212,200	4,916	4,171	3,753,900	8,342	5,148	4,633,200	10,296	8,127	7,314,300	16,254
		3 Low intensity	1,621	1,458,900	4,863	524	471,600	1,572	1,134	1,020,600	3,402	1,785	1,606,500	5,355	2,861	2,574,900	8,583
		4 Medium intensity	572	514,800	2,288	439	395,100	1,756	955	859,500	3,820	1,339	1,205,100	5,356	1,750	1,575,000	7,000
		5 High intensity	313	281,700	1,565	247	222,300	1,235	499	449,100	2,495	487	438,300	2,435	516	464,400	2,580
		Sum			**47,215**			**43,375**			**48,833**			**52,216**			**58,794**
	Road Network	1 No road	34,124	30,711,600	34,124	35,274	31,746,600	35,274	33,888	30,499,200	33,888	33,025	29,722,500	33,025	31,049	27,944,100	31,049
		2 Trail or Alley	396	356,400	792	204	183,600	408	503	452,700	1,006	482	433,800	964	484	435,600	968
		3 Local road	2,352	2,116,800	7,056	1,662	1,495,800	4,986	2,409	2,168,100	7,227	2,699	2,429,100	8,097	3,696	3,326,400	11,088
		4 Secondary road	554	498,600	2,216	316	284,400	1,264	381	342,900	1,524	479	431,100	1,916	933	839,700	3,732
		5 Highway	107	96,300	535	108	97,200	540	352	316,800	1,760	848	763,200	4,240	1,469	1,322,100	7,345
		Sum			**44,723**			**42,472**			**45,405**			**48,242**			**54,182**
		Sub-Total			**139,163**			**128,622**			**145,003**			**160,431**			**167,539**
Factor 3 (GR)	Aquifer	1 No aquifer	1,123	1,010,700	1,123	1,332	1,198,800	1,332	2,261	2,034,900	2,261	1,082	973,800	1,082	1,252	1,126,800	1,252
		2 Yegua-Jackson	2,392	2,152,800	4,784	1,142	1,027,800	2,284	1,087	978,300	2,174	1,216	1,094,400	2,432	1,042	937,800	2,084
		4 Edwards-Trinity / Carrizo-Wilcox	11,732	10,558,800	46,928	10,183	9,164,700	40,732	11,180	10,062,000	44,720	10,104	9,093,600	40,416	10,384	9,345,600	41,536
		5 Trinity / Gulf-Coast	22,286	20,057,400	111,430	24,907	22,416,300	124,535	23,005	20,704,500	115,025	25,131	22,617,900	125,655	24,953	22,457,700	124,765
		Sum			**164,265**			**168,883**			**164,180**			**169,585**			**169,637**
	Geology	1 Limestone	4,673	4,205,700	4,673	2,253	2,027,700	2,253	5,377	4,839,300	5,377	1,924	1,731,600	1,924	1,151	1,035,900	1,151
		2 Mudstone / Sandstone	4,756	4,280,400	9,512	3,406	3,065,400	6,812	5,874	5,286,600	11,748	3,954	3,558,600	7,908	3,493	3,143,700	6,986
		3 Gravel	262	235,800	786	3,175	2,857,500	9,525	730	657,000	2,190	3,103	2,792,700	9,309	3,757	3,381,300	11,271
		4 Clay	15,381	13,842,900	61,524	15,932	14,338,800	63,728	15,659	14,093,100	62,636	16,309	14,678,100	65,236	7,549	6,794,100	30,196
		5 Sand / Water	12,461	11,214,900	62,305	12,798	11,518,200	63,990	9,893	8,903,700	49,465	12,243	11,018,700	61,215	21,681	19,512,900	108,405
		Sum			**138,800**			**146,308**			**131,416**			**145,592**			**158,009**

(**Table 28** Continued)

Factor	Variable	Reclassification Score & Description	PATH01 Pixel Count	PATH01 Area (m2)	PATH01 Suitability Score	PATH02 Pixel Count	PATH02 Area (m2)	PATH02 Suitability Score	PATH03 Pixel Count	PATH03 Area (m2)	PATH03 Suitability Score	PATH04 Pixel Count	PATH04 Area (m2)	PATH04 Suitability Score	PATH05 Pixel Count	PATH05 Area (m2)	PATH05 Suitability Score
	Precipitation	1 Less than 35 inches	10,900	9,810,000	10,900	6,436	5,792,400	6,436	10,127	9,114,300	10,127	7,277	6,549,300	7,277	7,631	6,867,900	7,631
		2 35 inches < Precipitation < 40 inches	7,944	7,149,600	15,888	11,578	10,420,200	23,156	7,996	7,196,400	15,992	10,737	9,663,300	21,474	10,821	9,738,900	21,642
		3 40 inches < Precipitation < 45 inches	11,388	10,249,200	34,164	12,201	10,980,900	36,603	12,086	10,877,400	36,258	12,195	10,975,500	36,585	13,024	11,721,600	39,072
		4 45 inches < Precipitation < 50 inches	7,301	6,570,900	29,204	7,349	6,614,100	29,396	7,324	6,591,600	29,296	7,324	6,591,600	29,296	6,155	5,539,500	24,620
		5 Greater than 50 inches	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Sum			**90,156**			**95,591**			**91,673**			**94,632**			**92,965**
		Sub-Total			**393,221**			**410,782**			**387,269**			**409,809**			**420,611**
Factor 4 (WR)	Hydrology	1 No water features	36,197	32,577,300	36,197	36,276	32,648,400	36,276	36,211	32,589,900	36,211	36,753	33,077,700	36,753	35,939	32,345,100	35,939
		2 Brooks or Small streams	912	820,800	1,824	903	812,700	1,806	1,051	945,900	2,102	605	544,500	1,210	929	836,100	1,858
		3 Medium streams	179	161,100	537	138	124,200	414	135	121,500	405	65	58,500	195	577	519,300	1,731
		4 Large streams / Small water bodies	202	181,800	808	85	76,500	340	111	99,900	444	74	66,600	296	88	79,200	352
		5 Dam / Lake or Reservoirs	43	38,700	215	162	145,800	810	25	22,500	125	36	32,400	180	98	88,200	490
		Sum			**39,044**			**39,646**			**39,287**			**38,634**			**40,370**
	Floodplain	1 No floodplain	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		2 500 year with less than 0.2% probability	32,868	29,581,200	65,736	32,570	29,313,000	65,140	33,853	30,467,700	67,706	34,977	31,479,300	69,954	28,771	25,893,900	57,542
		3 Between 100 - 500 year	197	177,300	591	68	61,200	204	36	32,400	108	56	50,400	168	129	116,100	387
		4 100 year with depth less than 3ft	-	-	-	-	-	-	-	-	-	-	-	-	527	474,300	2,108
		5 100 year with more scrutiny	4,468	4,021,200	22,340	4,926	4,433,400	24,630	3,644	3,279,600	18,220	2,500	2,250,000	12,500	8,204	7,383,600	41,020
		Sum			**88,667**			**89,974**			**86,034**			**82,622**			**101,057**
	Wetland	1 No wetland	35,186	31,667,400	35,186	36,041	32,436,900	36,041	36,142	32,527,800	36,142	36,983	33,284,700	36,983	33,998	30,598,200	33,998
		4 Vegetation accounts for more than 20%	2,274	2,046,600	9,096	1,436	1,292,400	5,744	1,340	1,206,000	5,360	525	472,500	2,100	3,525	3,172,500	14,100
		5 Vegetation accounts for more than 80%	73	65,700	365	87	78,300	435	51	45,900	255	25	22,500	125	108	97,200	540
		Sum			**44,647**			**42,220**			**41,757**			**39,208**			**48,638**
		Sub-Total			**172,895**			**171,903**			**167,078**			**160,464**			**190,065**
Factor 5 (GS)	Slope	1 0.26 - 1.25%	8,304	7,473,600	8,304	11,552	10,396,800	11,552	11,017	9,915,300	11,017	12,959	11,663,100	12,959	17,138	15,424,200	17,138
		2 1.26 - 2.50%	3,204	2,883,600	6,408	3,437	3,093,300	6,874	2,952	2,656,800	5,904	3,156	2,840,400	6,312	3,063	2,756,700	6,126
		3 2.51 - 3.50%	12,436	11,192,400	37,308	11,932	10,738,800	35,796	11,735	10,561,500	35,205	10,984	9,885,600	32,952	10,374	9,336,600	31,122
		4 Less than 0.25%	4,221	3,798,900	16,884	3,585	3,226,500	14,340	3,926	3,533,400	15,704	3,300	2,970,000	13,200	2,641	2,376,900	10,564
		5 Greater than 3.51%	9,368	8,431,200	46,840	7,058	6,352,200	35,290	7,903	7,112,700	39,515	7,134	6,420,600	35,670	4,415	3,973,500	22,075
		Sum			**115,744**			**103,852**			**107,345**			**101,093**			**87,025**
	Vegetation	1 No vegetation	8,594	7,734,600	8,594	5,501	4,950,900	5,501	8,297	7,467,300	8,297	9,492	8,542,800	9,492	19,769	17,792,100	19,769
		2 Barren land	72	64,800	144	26	23,400	52	99	89,100	198	88	79,200	176	46	41,400	92
		3 Pasture / Grassland	14,858	13,372,200	44,574	19,947	17,952,300	59,841	17,136	15,422,400	51,408	18,274	16,446,600	54,822	11,331	10,197,900	33,993
		4 Crops	1,701	1,530,900	6,804	1,444	1,299,600	5,776	1,820	1,638,000	7,280	1,381	1,242,900	5,524	526	473,400	2,104
		5 Forest / Shrubs	12,308	11,077,200	61,540	10,646	9,581,400	53,230	10,181	9,162,900	50,905	8,298	7,468,200	41,490	5,959	5,363,100	29,795
		Sum			**121,656**			**124,400**			**118,088**			**111,504**			**85,753**
	Farm Employees	1 Employees less than 250	3,653	3,287,700	3,653	1,877	1,689,300	1,877	4,761	4,284,900	4,761	4,774	4,296,600	4,774	7,244	6,519,600	7,244
		2 250 < Employees < 540	10,920	9,828,000	21,840	9,392	8,452,800	18,784	9,722	8,749,800	19,444	8,833	7,949,700	17,666	9,101	8,190,900	18,202
		3 540 < Employees < 720	8,389	7,550,100	25,167	7,839	7,055,100	23,517	5,620	5,058,000	16,860	6,403	5,762,700	19,209	9,134	8,220,600	27,402
		4 720< Employees < 860	7,516	6,764,400	30,064	6,680	6,012,000	26,720	3,913	3,521,700	15,652	6,129	5,516,100	24,516	5,419	4,877,100	21,676
		5 Employees more than 860	7,055	6,349,500	35,275	11,776	10,598,400	58,880	13,517	12,165,300	67,585	11,394	10,254,600	56,970	6,733	6,059,700	33,665
		Sum			**115,999**			**129,778**			**124,302**			**123,135**			**108,189**
		Sub-Total			**353,399**			**358,030**			**349,735**			**335,732**			**280,967**
		Grand Total			**1,306,809**			**1,352,802**			**1,328,476**			**1,347,146**			**1,340,109**

(Numbers in **red** indicates the least suitable route and in **blue** indicates the most suitable option)

5.1.1 Value Approximation: Variables in Factor 1

Path 5, having the highest score, is the lowest suitable option for the Population Density variable. It means that this route has the highest probability of relocating people and goods. As can be seen in Table 29, implementing Path 5 will require about 840 acres of highly populated areas. In terms of Job Density, Path 5 will consume 990 acres of job sites where the job density is greater than 4.3 jobs per acre. Finally, Path 2 cuts through lands with the highest occupancy rates. As can be seen below, Path 2 passes through 3,743 acres (2,203 + 1,540 acres) of land where the occupancy rate is greater than 80%. This is 1,894 acres more than Path 1 in the same category.

Table 29 Value Approximation for Factor 1 Variables

		PATH1	PATH2	PATH3	PATH4	PATH5
	Score	Acres	Acres	Acres	Acres	Acres
Pop. Density	1.0	82	85	81	81	85
	2.0	7,178	7,212	7,142	6,986	7,035
	3.0	809	470	302	459	294
	4.0	121	444	684	679	287
	5.0	158	143	138	142	667
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Job Density	2.0	7,608	7,333	7,449	7,449	7,154
	3.0	739	719	305	305	225
	4.0	-	302	248	237	928
	5.0	-	-	345	356	62
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Occupancy Rate	1.0	3,127	1,326	1,309	1,399	1,925
	2.0	1,657	1,095	1,504	1,337	754
	3.0	1,714	2,190	2,550	2,648	3,404
	4.0	1,097	2,203	1,981	1,801	1,126
	5.0	752	1,540	1,003	1,162	1,159
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**

5.1.2 Value Approximation: Variables in Factor 2

Path 5 indicates the highest scores (lowest suitability) in the variables of Factor 2 as well. As can be seen in Table 30, by implementing Path 5, 389 acres of highly-developed land and 636 acres of medium-developed land are consumed by that HSR route. In addition, it would also interfere with 327 acres of major highways and 207 acres of secondary roads such as county highways. Compared to Path 2, which consumes the least amount of land in terms of the Land Use and Road Network variables, Path 5 consumes about 291 more acres of highly-developed land uses and 303 more acres of primary highways. If the built environment is our highest concern when selecting the route, these numbers indicate a substantial difference between Path 2 and 5.

Table 30 Value Approximation for Factor 2 Variables

		PATH1	PATH2	PATH3	PATH4	PATH5
	Score	Acres	Acres	Acres	Acres	Acres
Noise	1.0	7,730	8,005	7,485	6,913	7,299
	3.0	121	105	202	279	174
	4.0	72	**28**	100	**187**	165
	5.0	425	**217**	560	**968**	730
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Land Use	2.0	7,018	7,538	6,844	6,399	5,421
	3.0	772	547	928	1,145	1,807
	4.0	360	**117**	252	397	**636**
	5.0	127	**98**	212	298	**389**
	SUM	**8,277**	**8,299**	**8,236**	**8,239**	**8,254**
Road Network	1.0	7,589	7,845	7,536	7,344	6,905
	2.0	88	45	112	107	108
	3.0	523	370	536	600	822
	4.0	123	**70**	85	107	**207**
	5.0	24	**24**	78	189	**327**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**

5.1.3 Value Approximation: Variables in Factor 3

For the variables in Factor 3, Ground Resources, the paths range over a wide spectrum of values. For example, Path 4 shows the highest probability of contaminating two of the state's largest aquifers, the Trinity and Gulf-Coast Aquifers, by covering 5,589 acres of the ground above. On the other hand, Path 4 is the best option for avoiding the Edward-Trinity Aquifer, covering just 2,247 acres above it. Compared to Path 1, which consumes the most amounts of land above the Edward-Trinity Aquifer, it is 362 acres less. Regarding the Geology variable, Path 5 has the highest likelihood of coming across water or sand, crossing 4,822 acres. Path 4 has the highest probability of crossing clay (3,627 acres). In both cases, Paths 4 and 5 may encounter difficulties in construction suitability with due to geologic units. When considering the variable of Precipitation, Path 2 shows the least suitability, passing about 1,634 acres of land receiving over 45 inches of precipitation a year, the highest record. Table 31 summarizes the result.

Table 31 Value Approximation for Factor 3 Variables

		PATH1	PATH2	PATH3	PATH4	PATH5
	Score	Acres	Acres	Acres	Acres	Acres
Aquifer	1.0	250	296	503	241	278
	2.0	532	254	242	270	232
	4.0	**2,609**	2,265	2,486	**2,247**	2,309
	5.0	**4,956**	5,539	5,116	**5,589**	5,549
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Geology	1.0	1,039	501	1,196	428	256
	2.0	1,058	757	1,306	879	777
	3.0	58	706	162	690	836
	4.0	3,421	3,543	3,482	**3,627**	**1,679**
	5.0	2,771	2,846	**2,200**	2,723	**4,822**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Precipitation	1.0	2,424	1,431	2,252	1,618	1,697
	2.0	1,767	2,575	1,778	2,388	2,406
	3.0	**2,533**	2,713	2,688	2,712	**2,896**
	4.0	1,624	**1,634**	1,629	1,629	**1,369**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**

5.1.4 Value Approximation: Variables in Factor 4

Table 32 shows the value approximation for the variables in Factor 4. Path 5 consumes 22 acres of land scoring a 5 in the Hydrology variable, which indicates Lake or Reservoirs. In other words, this path would require a substantive amount of extra structures to implement or may even be impossible to build, if the route interferes with a dam structure. Path 1 requires crossing 45 acres of large streams or small-sized water bodies. Path 5 also covers 1,824 acres of land scoring the highest probability of flooding (100 year with the highest scrutiny), and 117 acres of lands with 100 year. Considering that Path 4 requires no lands within this category and only 556 acres for the areas with the highest scrutiny (a difference of 1,269 acres), this is quite a substantive amount. Finally, Path 5 also consumes the most acreage within the Wetland variable, 24 acres of wetlands with vegetation covering more than 80% of the area as well as 784 acres of wetland with vegetation covering more than 20%. The difference between Paths 4 and 5 for the score 5 category is 18 acres, and for the score 4 category is 667 acres.

Table 32 Value Approximation for Factor 4 Variables

		PATH1	PATH2	PATH3	PATH4	PATH5
	Score	Acres	Acres	Acres	Acres	Acres
Hydrology	1.0	8,050	8,067	8,053	8,173	7,992
	2.0	203	201	234	135	207
	3.0	40	31	30	14	128
	4.0	**45**	19	25	**16**	20
	5.0	10	36	**6**	8	**22**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Floodplain	2.0	7,310	7,243	7,529	7,779	6,398
	3.0	44	15	8	12	29
	4.0	**0**	**0**	**0**	**0**	**117**
	5.0	994	1,095	810	**556**	**1,824**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Wetland	1.0	7,825	8,015	8,038	8,225	7,561
	4.0	506	319	298	**117**	**784**
	5.0	16	19	11	**6**	**24**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**

5.1.5 Value Approximation: Variables in Factor 5

The last value approximation is for the variables in Factor 5. Table 33 illustrates the result, and Path 5 shows the most suitable fit. Path 1 requires 2,083 acres of lands that are above 3.5% slope and 939 acres with less than 0.25% slope. On the contrary, Path 5 consumes 982 acres of lands that are above 3.5% grade and 587 acres with a grade of less than 0.25%. The differences between the two for the least suitable slope are 1,101 acres (2,038 – 982 acres). In terms of the Vegetation variable, Path 1 consumes 2,737 acres of Forest or Shrubs, whereas Path 5 only consumes 1,325 acres (1,412 acres difference). For the Crop areas, Path 5 consumes 117 acres of crops and Path 3 requires

405 acres. Finally, Path 3 impinges upon 3,006 acres of farmlands with employment greater than 860 employees, and Path 1 hinders the operation of 1,671 acres of farmland employing between 720 and 860 workers. This is substantive as Path 5 requires 1,497 acres for farmland with more than 860 employees, and Path 3 requires 870 acres of farmland employing between 720 and 860 workers. If productive farmland is considered the key criterion, this implies a substantive result.

Table 33 Value Approximation for Factor 5 Variables

		PATH1	PATH2	PATH3	PATH4	PATH5
	Score	Acres	Acres	Acres	Acres	Acres
Slope	1.0	1,847	2,569	2,450	2,882	3,811
	2.0	713	764	656	702	681
	3.0	2,766	2,654	2,610	2,443	2,307
	4.0	**939**	797	873	734	**587**
	5.0	**2,083**	1,570	1,758	1,587	**982**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Vegetation	1.0	1,911	1,223	1,845	2,111	4,396
	2.0	16	6	22	20	10
	3.0	3,304	4,436	3,811	4,064	2,520
	4.0	378	321	**405**	307	**117**
	5.0	**2,737**	2,368	2,264	1,845	**1,325**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**
Farms	1.0	812	417	1,059	1,062	1,611
	2.0	2,428	2,089	2,162	1,964	2,024
	3.0	1,866	1,743	1,250	1,424	2,031
	4.0	**1,671**	1,486	**870**	1,363	1,205
	5.0	1,569	2,619	**3,006**	2,534	**1,497**
	SUM	**8,347**	**8,354**	**8,347**	**8,347**	**8,369**

5.1.6 Value Approximation Summary

Based solely on suitability scores, Path 1 and Path 2 seem to be the most suitable options, while Path 5 appears to be the least desirable. As can be seen in Table 34, Path 5 indicated the least suitable scores (classification 5) in seven categories with another six falling under classification 4. In other words, implementing Path 5 in the study area may increase conflicts with 13 variables. On the other hand, Path 1 shows only two categories scoring the least suitable scores, and three more with a classification 4. Paths 1 and 2 illustrate the most suitable matches in the toughest conditions, which are suitability scores greater than 3 in all variables.

This does not decisively mean, however, that Paths 1 or 2 are the most sustainable corridors and Path 5 is the worst. Scrutinizing suitability scores alone gives different implications than visual examination. As can be seen, similarly shaped Paths 2, 3, and 4 all possess different suitability scores and consume different amounts of the input variables. In this sense, comparing each path's costs would be more a logical way to come to a decision on an HSR route. For the subsequent steps, construction costs, which include land acquisition costs, will be estimated based on given specifications, and operation and maintenance costs will also be estimated. Finally, associated environmental costs will be analyzed to compare each route in terms of externalities.

Table 34 Value Approximation Summary

Score	Suitability	Population Density	Job Density	Occupancy Rate	Noise
4	Most	Path1	Path1	Path1	Path2
	Least	Path3	Path5	Path2	Path4
5	Most	Path3	Path 1 & 2	Path1	Path2
	Least	Path5	Path4	Path2	Path4
		Land Use	**Road Network**	**Aquifer**	**Geology**
4	Most	Path2	Path2	Path4	Path5
	Least	Path5	Path5	Path1	Path4
5	Most	Path2	Path2	Path1	Path3
	Least	Path5	Path5	Path4	Path5
		Precipitation	**Hydrology**	**Floodplain**	**Wetland**
4	Most	Path1	Path4	Path1-4	Path4
	Least	Path2	Path1	Path5	Path5
5	Most	Path5	Path3	Path4	Path4
	Least	Path2	Path5	Path5	Path5
		Slope	**Vegetation**	**Farms**	
4	Most	Path5	Path5	Path3	
	Least	Path1	Path3	Path1	
5	Most	Path5	Path5	Path5	
	Least	Path1	Path1	Path3	

5.2 Construction Cost Estimate

According to the Korean HSR specification, construction costs largely consist of three elements: 1) hardware construction cost; 2) software construction cost; and 3) land acquisition cost. Both hardware and software construction estimates were provided by POSCO Engineering and Construction Co., Ltd. when the firm fully funded the TUT research for six months in 2011. Cost information is for the Korean HSR and in Korean currency. This information was converted to U.S. dollars using November 15, 2012 currency information (CNNMoney 2012). Table 35 indicates this information.

Table 35 Construction Cost Estimate of Korean HSR

Currency as of Nov. 15 2012: $1.00 = ₩1,088.27			Korean Won / km	$ / km	$ / mile
Hardware Estimate	Civil Work	Normal	9,900,000,000	9,096,989	14,555,182
		Soft Soil	12,800,000,000	11,761,764	18,818,822
	Bridge Structures	Normal	30,300,000,000	27,842,300	44,547,680
		Over Bridge	3,400,000,000	3,124,218	4,998,749
	Station	Civil	14,100,000,000	12,956,318	20,730,109
		Structure	68,700,000,000	63,127,592	101,004,147
	Facility	Track Facilities	3,700,000,000	3,399,884	5,439,814
		General Facilities	1,900,000,000	1,745,886	2,793,418
		Electrical Facilities	600,000,000	551,332	882,131
		Signal Facilities	900,000,000	826,999	1,323,198
		Communication Facilities	1,000,000,000	918,887	1,470,219
	Miscellaneous		2,300,000,000	2,113,441	3,381,506
	SUM		**30,600,000,000**	**28,117,962**	**44,988,739**
Software Estimate	Electronic Systems	Transmission Lines	273,000,000	250,856	401,370
		Electricity Station	894,000,000	821,485	1,314,376
		Traction Lines	912,000,000	838,025	1,340,840
		Power Utilities	695,000,000	638,627	1,021,803
	Signal Systems	Automatic Train Control	1,097,000,000	1,008,019	1,612,830
		Interlocking Devices	607,000,000	557,764	892,422
		Centralized Traffic Control	188,000,000	172,750	276,400
	Telecommunication Systems	Transmission network	417,000,000	383,176	613,082
		Telecommunication Facilities for Station	600,000,000	551,332	882,131
		Wireless Facilities for Train	333,000,000	305,989	489,582
		Communication Inductive Device	179,000,000	164,480	263,168
	SUM		**6,195,000,000**	**5,692,503**	**9,108,005**
GRAND TOTAL			**36,795,000,000**	**33,810,465**	**54,096,744**

As there is no need to construct a tunnel in the study area, no cost information on tunnel construction is incorporated into this study. In addition, as there are only two stations in this study boundary, the cost estimate for stations is essentially a fixed cost for all the route options.

There are differences in civil work and bridge structures, however, as each route will be built on different geologic conditions. For example, Path 5 passes 21,681 pixels (4,822 acres) of Sand or Water, which can be considered soft soil, whereas Path 3 only consumes 9,893 pixels (2,200 acres) of the same geologic units. For Path 5, for which the total number of pixels in its path representing the Geology variable is 37,631, this amounts about 57.6% (or 143.6 km when 249.3 km is multiplied by 0.576) of the entire route that is on soft soils. Table 36 illustrates the conversion of pixels into length for each path. Furthermore, we can calculate a cost estimate for the construction required atop soft soil based on this length information. For more detailed calculation, refer to Table 36.

Table 36 Total Length and Pixel Count for Each Path

	Path1	Path2	Path3	Path4	Path5
In kilometers	241.5 km	233.6 km	239.2 km	233.6 km	249.3 km
In miles	150 miles	145 miles	149 miles	145 miles	155 miles
Total Pixel Count	37,533	37,564	37,533	37,533	37,631

The same logic applies to bridge structures. A normal bridge is required when a route passes medium to large streams, information that can be retrieved from the Hydrology variable. As can be seen in the suitability score matrix (Table 28), Path 5 passes about 665 pixels of medium and large streams (577 medium streams + 88 large streams). On the other hand, Path 4 only consumes 139 pixels of the same stream categories (65 medium streams + 74 large streams). Using this information, the total length of bridge construction can be estimated. Approximately 1.76% (about 4.39 km) of Path 5 crosses medium and large streams and will require bridge structures. For more detailed information, refer to Table 37.

Another type of bridge, the overpass bridge, is required when an HSR route passes across major highways or main roads, and this can be assessed using the Road Network variable. For instance, Path 5 passes 1,469 pixels of major highways in the Road Network variable, whereas Path 2 only consumes 108 pixels. If converted into length, Path 5 requires about 3.9% (about 9.7 km) of the route be built over major highways, while Path 2 requires 0.29% (about 0.7 km) for the same classification. For the detailed calculation, refer to Table 38.

Other than these two cost categories of civil works and bridge construction, most other cost items remain the same, although total length of each route is another factor. Using the information in Table 35 and the suitability matrix, construction cost estimates for each route are calculated.

5.2.1 Civil Work Cost Estimate

The cost of civil work is based on the Geology variable. To identify the soft soil areas, reclassification scores of 4 (Clay), and 5 (Sand or Water) are used. Table 37 indicates possible costs for civil work for each route. It also calculates the number of pixels in each path representing the Geology variable.

As can be seen, the costs range from about $2.6 billion to $2.8 billion. Path 5 requires the highest cost in terms of civil work because Path 5 consumes the greatest area of soft ground. The total cost for the civil work indicates that Path 4 is the least costly option by approximately $185 million compared to Path 5.

Table 37 Civil Work Cost Estimate for Each Path

	(in million $)	PATH01		PATH02		PATH03		PATH04		PATH05	
	Geology Variable	Pixels	%	Pixels	%	Pixels	%	Pixels	%	Pixels	%
Normal	Limestone	4,673	12.45%	2,253	6.00%	5,377	14.33%	1,924	5.13%	1,151	3.06%
	Mudstone / Sandstone	4,756	12.67%	3,406	9.07%	5,874	15.65%	3,954	10.53%	3,493	9.28%
	Gravel	262	0.70%	3,175	8.45%	730	1.94%	3,103	8.27%	3,757	9.98%
	SUM	9,691	25.82%	8,834	23.52%	11,981	31.92%	8,981	23.93%	8,401	22.32%
	Length (proportional)		62.36km		54.94km		76.36km		55.90km		55.66km
	Civil Cost		**$567.3**		**$499.8**		**$694.6**		**$508.5**		**$506.3**
Soft Soil	Clay	15,381	40.98%	15,932	42.41%	15,659	41.72%	16,309	43.45%	7,549	20.06%
	Sand / Water	12,461	33.20%	12,798	34.07%	9,893	26.36%	12,243	32.62%	21,681	57.61%
	SUM	27,842	74.18%	28,730	76.48%	25,552	68.08%	28,552	76.07%	29,230	77.68%
	Length (proportional)		179.14km		178.66km		162.84km		177.70km		193.64km
Civil Cost			**$2,107.0**		**$2,101.4**		**$1,915.3**		**$2,090.1**		**$2,277.5**
	Total		**$2,674.3**		**$2,601.2**		**$2,609.9**		**$2,598.6**		**$2,783.8**

5.2.2 Bridge Structure Cost Estimate

As briefly discussed earlier, estimating the costs of bridges is a two-part process. First, structures under normal circumstance need to be assessed. After that, structures passing over existing roads should be quantified. In order to measure these two aspects, we use the Hydrology variable, calculating the total number of pixels scored a 3 or 4, medium and large streams that require bridge structures under normal circumstances. Hence, the number of pixels and their proportion to the total number of pixels will be assessed.

After that, structures requiring over bridges are identified. This time using the Road Network variable, pixels scoring a 4 or 5, Secondary Road and Highways are selected and quantified. According to the Feature Class Code (FCC), highways indicate interstate highways, and the secondary road implies state and county highways, which are sizable enough to require overpass bridges. Table 38 depicts the number of pixels for both the Hydrology and Road Network variables that each path passes through. In addition, each path's possible bridge structure cost estimates are calculated in proportion to the total length of the routes.

Table 38 Bridge Structure Cost Estimate for Each Path

	(in million $)	Path1		Path2		Path3		Path4		Path5	
		Pixels	%	Pixels	%	Pixels	%	Pixels	%	Pixels	%
Normal	Medium streams	179	0.48%	138	0.37%	135	0.36%	65	0.17%	577	1.53%
	Large streams / Small water bodies	202	0.54%	85	0.23%	111	0.30%	74	0.20%	88	0.23%
	SUM	381	1.02%	223	0.59%	246	0.66%	139	0.37%	665	1.77%
	Length (proportional)		2.45km		1.39km		1.57km		0.87km		4.41km
	Bridge Cost		**$68.15**		**$38.70**		**$43.58**		**$24.05**		**$122.47**
Over Bridge	Secondary road	554	1.48%	316	0.84%	381	1.02%	479	1.28%	933	2.48%
	Highway	107	0.29%	108	0.29%	352	0.94%	848	2.26%	1,469	3.90%
	SUM	661	1.76%	424	1.13%	733	1.95%	1,327	3.54%	2,402	6.38%
	Length (proportional)		4.25km		2.64km		4.67km		8.26km		15.91km
	Bridge Cost		**$13.27**		**$8.25**		**$14.57**		**$25.77**		**$49.65**
Total			**$81.42**		**$48.81**		**$58.16**		**$49.82**		**$172.12**

As can be seen in Table 38, Path 5 shows the most costly option in terms of bridge structures. This is because Path 5 requires around 4.4km of normal bridge structures, whereas the remaining routes need less than 2.5km. In addition, Path 5 also crosses 15.9km of major roads, necessitating overpass bridges. On the other hand, Path 2, which is the least costly option when considering just bridge structures, requires 1.39km for normal bridges and 2.64km for over bridges. Accordingly, Path 2 will need about $49 million to build the bridges, while Path 5 would require $172 million for a difference of approximately $123 million.

5.2.3 Other Cost Estimate

Unlike civil work and bridge structure costs, facility and miscellaneous costs do not differ based on each path's attributes. Therefore, it is easier to calculate these two costs in terms of each path's total length. Table 39 summarizes the result. Because the cost estimates are based on total length, Path 5 again implies the most expensive option with Paths 2 and 4 trying for the lowest cost alternatives.

Table 39 Other Cost Categories Estimate for Each Path

	(in million $)	Path1	Path2	Path3	Path4	Path5
	Total Length	241.5km	233.6km	239.2km	233.6km	249.3km
Hardware	Facility	$1,797.5	$1,738.7	$1,780.3	$1,738.7	$1,855.5
	Miscellaneous	$510.4	$493.7	$505.5	$493.7	$526.9
	SUM	**$2,307.9**	**$2,232.4**	**$2,285.8**	**$2,232.4**	**$2,382.4**
Software	Electronic Systems	$615.6	$595.4	$609.7	$595.4	$635.5
	Signal Systems	$419.9	$406.1	$415.9	$406.1	$433.4
	Telecommunication	$339.3	$328.2	$336.1	$328.2	$350.3
	SUM	**$1,374.8**	**$1,329.7**	**$1,361.7**	**$1,329.7**	**$1,419.2**
	TOTAL	**$3,682.7**	**$3,562.1**	**$3,647.5**	**$3,562.1**	**$3,801.6**

5.2.4 Land Acquisition Cost Estimate

The cost of land acquisition can be estimated using parcel level data, which is provided by county appraisal districts. The main obstacle in obtaining the datasets is that some counties provide for free-of-charge, whereas others' must be purchased. For example, large-sized counties, such as Travis and Harris provide their parcel data without any cost. On the other hand, small counties like Fayette and Lee sell datasets in a CD format varying from $10 to $250 each. Precisely speaking, Fayette County charges $250 and Lee County $75 for their parcel level datasets. To reduce financial burdens and to save time, an alternative way to account for land acquisition costs was used.

Based on conversation with the committee members, a median housing value was determined that could be used as a proxy value to estimate land acquisition costs. Although the median housing value is not as detailed as the parcel datasets, such data acquired by the county appraisal district do not necessarily reflect market value as well. Instead, they are appraised values, which often give false impressions of the true market values. Because of this, using a median value was deemed representative enough of land acquisition costs that satisfies as a proxy measure to substitute parcel level datasets. The U.S. Census Bureau provides the median housing values within the study area at census tract level and in 2011 format. Since median values are based on the American Community Survey (ACS), they also contain the upper and lower margins for each value.

The cost estimate of land acquisition using the median housing value is done in four steps. First, the median housing values for each census tract is collected from the U.S. Census Bureau's American Community Survey (ACS). After that, the number of housing units in each census tract ascertained from the U.S. Census Bureau's 2010 SF1 dataset is counted. Accordingly, median values are multiplied by the number of housing units, giving a basic interpretation of total housing values in each census tract. Third, the area of each path (rail track) alternative is measured, while the total area of census tracts intersected by each path is simultaneously quantified. Using the area of ROW and the area of intersected census tracts, the proportion of route area to census tract areas is calculated.

Finally, total housing values are multiplied by the proportion obtained above for each path option. The main reason for doing so is to avoid exaggerating the land acquisition estimate. A census tract can be fairly sizeable, so a census tract intersecting with a path may not necessarily need to be purchased as a whole. If only a small portion of a tract is intersected by a path alternative, then the acquisition amount should be less than the census tracts' total value as the entire census tracts' area will not be necessary to routing. Figures 35(a) through 35(e) illustrate the different census tracts intersected by each route.

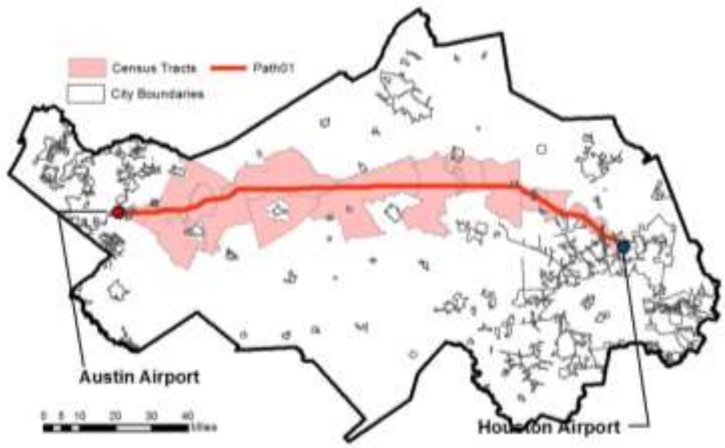


Figure 35(a) Census Tracts Intersected by Path 1

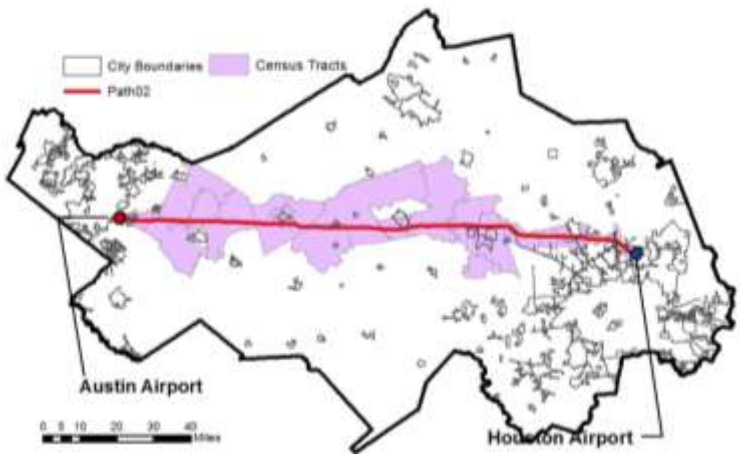


Figure 35(b) Census Tracts Intersected by Path 2

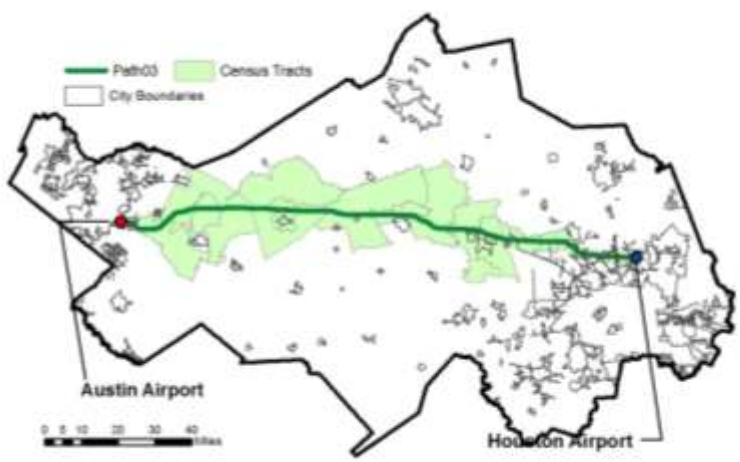


Figure 35(c) Census Tracts Intersected by Path 3

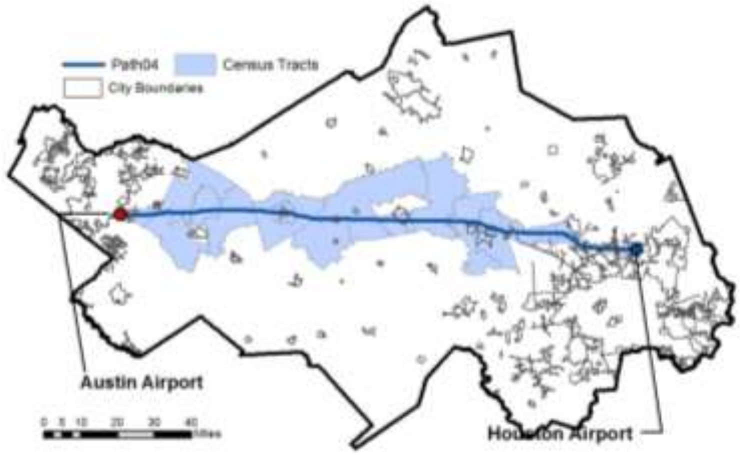


Figure 35(d) Census Tracts Intersected by Path 4

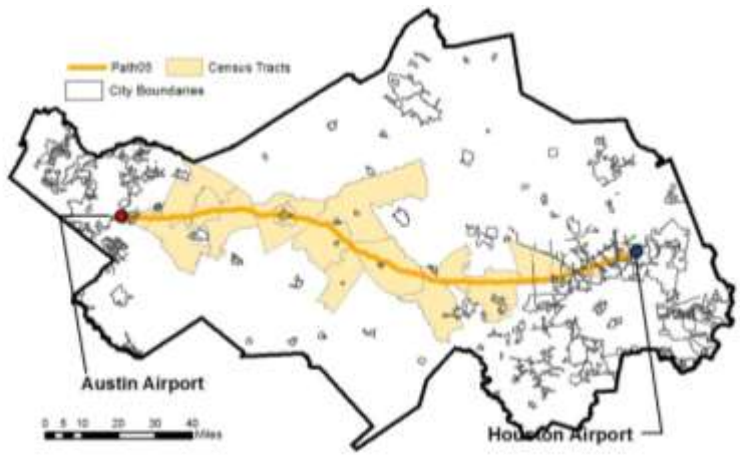


Figure 35(e) Census Tracts Intersected by Path 5

Table 40 summarizes the result of land acquisition costs using the median housing values for each census tract. Path 5 passes the most tracts and housing units, whereas Paths 2 and 4 pass the fewest tracts and Path 1 intersects the fewest amounts of housing units. Total median housing values are calculated using the number of units in each census tract and their median values. For example, if there are 20 housing units in a census tract and its median housing value is $10,000, then the total median housing value is $200,000 (20 units x $10,000). A proportion is calculated by dividing the total area of train tracks by the total area of intersected census tracts for each path option.

Finally, the proportional housing value is acquired by multiplying the proportion obtained above by the total median housing values.

As evident in Table 40, land acquisition cost is estimated to be the highest for Path 5, while Path 3 necessitates the lowest cost. Although Path 5 passes mostly through rural areas, the number of housing units disturbed by the route is greater than any of the other alternatives. Accordingly, the total median housing value is substantially greater than it is along other paths.

Table 40 Land Acquisition Estimate for Each Path

	Path1	Path2	Path3	Path4	Path5
No. of Census Tracts	36	**34**	35	**34**	**46**
No. of Housing Units	**85,231**	92,593	95,354	91,413	103,484
Total Median Housing Values (1)	$12,308.3M	$12,797.2M	$12,894.7M	$13,911.1M	$84,742.9M
Area of Census Tracts Combined (2)	1,184,377	1,172,271	1,242,470	1,180,624	1,291,629
Area of Train Track (3)	3,576	3,460	3,542	3,460	3,684
Proportion to Total Tract Area (4) = [(3) / (2)] x 100	0.302%	0.295%	0.285%	0.293%	0.285%
Proportional Housing Values = (4) x (1)	$37,171,042	$37,751,851	**$36,750,004**	$40,759,567	**$241,517,295**

It should be noted that these numbers are a conservative estimate. Because the median housing values are used as a proxy measure of the land acquisition cost, Table 40 would probably represent the least possible cost for compensation fees. Although proportional values are used to determine the anticipated acquisition cost, the precise number of houses needing to be relocated in order to build the HSR route is unaccounted for. Using the median values and proportional costs gives one possible solution to estimate the acquisition cost for each route alternative, but it should be interpreted with caution and considered a conservative measure.

5.2.5 Summary of Construction Cost Estimate

Aggregating the three elements together, total construction cost estimates are assessed. As can be seen in Table 41, Path 5 indicates the highest estimate of construction cost, whereas Path 2 is the lowest. If Path 5 is to be built, at least $7 billion would be required. Furthermore, this can be considered a conservative measure as the valuation was done in pixels and the land compensation fee is calculated using the median values. On the other hand, Path 2 would require $6.25 billion, a difference from Path 5 of about $752 million.

Table 41 Total Construction Cost Estimate for Each Path

(in million $)		Path1	Path2	Path3	Path4	Path5
Total Length		241.5km	233.6km	239.2km	233.6km	249.3km
Hardware	Normal Ground	$567.30	$499.80	$694.60	$508.50	$506.30
	Soft Ground	$2,107.00	$2,101.40	$1,915.30	$2,090.10	$2,277.50
	Normal Bridge Cost	$68.15	$38.70	$43.71	$24.22	$122.78
	Over Bridge Cost	$13.27	$8.25	$14.59	$25.81	$49.71
	Facility	$1,797.50	$1,738.70	$1,780.30	$1,738.70	$1,855.50
	Miscellaneous	$510.40	$493.70	$505.50	$493.70	$526.90
	SUM	**$5,063.66**	**$4,880.48**	**$4,954.13**	**$4,880.99**	**$5,338.79**
Software	Electronic Systems	$615.60	$595.40	$609.70	$595.40	$635.50
	Signal Systems	$419.90	$406.10	$415.90	$406.10	$433.40
	Telecommunication	$339.30	$328.20	$336.10	$328.20	$350.30
	SUM	**$1,374.74**	**$1,329.76**	**$1,361.65**	**$1,329.76**	**$1,419.14**
Land Acquisition		$37.17	$37.75	**$36.75**	$40.76	**$241.52**
Grand Total		**$6,475.57**	**$6,247.99**	**$6,352.53**	**$6,251.53**	**$6,999.45**
Difference		+$227.57	-	+$104.53	+$3.53	+$751.46

Path 2 resulting in the least costly option under construction cost considerations makes sense as it is designed to favor built environment variables such as road networks. An interesting outcome is that Path 4, intended to detour around water resource variables, is the second most feasible option in terms of construction cost estimate. The main reason for this is that the total length of Paths 2 and 4 are the same and some of the construction categories, such as software costs, are based on length.

5.3 Operation Cost Estimate

Operation cost is one of three measures to calculate the total costs for each route alternative. Operation cost includes costs associated with HSR operation and maintenance. To accurately measure the costs associated with HSR operation and maintenance, variable and fixed costs are assessed. Again, the datasets are for Korean HSR specifications and provided by the same sponsor.

Social cost is another element on which this study elaborates. In general, studies calculating social costs compare different transportation options such as airplane vs. rail, or highway vs. airplane. In this case, however, the study compares route options for only one means of transportation, so other social cost comparisons, such as congestion, accidents, or energy are not necessary. Therefore, the only social cost associated with HSR operation that varies by route would be the value of time, which is measured according to the different degrees of ridership levels.

5.3.1 Variable & Fixed Costs

According to the literature and the datasets received from the sponsor, operation cost of an HSR can be divided into two categories (Seo 2000; Rocky Mountain Rail Authority 2010): 1) variable costs and 2) fixed costs. Variable costs change with the volume of activity and are directly dependent on the volume of ridership, usually measured in passenger miles or train miles. On the other hand, fixed costs are predetermined and should remain stable across the route alternatives. In the Korean HSR case, variable costs include track maintenance costs, communication and signal costs, vehicle costs, and energy costs. Fixed costs consist of employment and administration costs.

Table 42 explains the Korean HSR operation and maintenance costs provided by the sponsor. As can be seen, the variable costs are an accumulation of four different cost attributes, totaling $1,100,202 per kilometer of HSR track. On the other hand, fixed costs are made up of two dominant categories, totaling $148,582,896 per year. As were construction cost estimates in Table 35, all of the cost information is converted to U.S. dollar using November 15, 2012 currency information (CNNMoney 2012).

Table 42 Operation & Maintenance Cost Estimate of Korean HSR

	Cost Category	Korean Won / km	U.S. Dollar / km
Variable Costs ($/km/year)	Track maintenance Costs	₩80,825,242.7	$74,268.7
	Telecommunication & Signal Maintenance Costs	₩197,087,378.6	$181,099.7
	Vehicle Maintenance Costs	₩292,475,728.2	$268,750.1
	Energy & Fuel Costs	₩234,466,019.4	$215,446.1
	SUM	**₩1,197,330,097.1**	**$1,100,202.7**
Fixed Costs ($/year)	Operation Crew Costs	₩97,400,000,000	$89,498,912.0
	Administration Costs	₩64,300,000,000	$59,083,984.0
	SUM	**₩161,700,000,000**	**$148,582,896.0**

(Currency as of November 15, 2012: $1.00 = ₩1,088.27)

Using the above information, each alternative's anticipated operation and maintenance costs are calculated. Table 43 indicates each path's annual operation and maintenance cost estimates. Because this estimate is based on train miles, it is quite expected to have Path 5 as the most costly option and Paths 2 and 4 as the least costly. The difference between the two options is around $17.3 million per year. This could be a significant factor in the decision-making process as the conventionally accepted return-on-investment period for a transportation investment in the U.S. is 20 to 50 years (Hayashi and Morisugi 2000; Lee 2000). In other words, Path 5 may consume around $346 million to $865 million more than Paths 2 and 4 in maintenance and operation costs during a 20-to-50 year time span.

Table 43 Operation & Maintenance Cost Estimate for Each Path

(million $ / year)	Length (km)	Variable Costs	Fixed Costs	Total
Path1	241.5km	$265.7	$148.6	$414.3
Path2	233.6km	$257.0	$148.6	**$405.6**
Path3	239.2km	$263.2	$148.6	$411.8
Path4	233.6km	$257.0	$148.6	**$405.6**
Path5	249.3km	$274.3	$148.6	**$422.9**

5.3.2 Value of Time

In addition to the variable and fixed costs, there is one more consideration in the operational aspect of an HSR. Because operations of an HSR are based on train-mile-traveled, value of time should be measured in the same regard. Value of time may not seem to be a significant factor in cost comparison. However, because the study area is so large - with each side of the Texas Urban Triangle measuring longer than 400km on average - a small change in operations could induce significant difference in total costs and ridership. Therefore, value of time should be included in the operation costs measure.

According to past studies (Hayashi and Morisugi 2000; Lee 2000; Morisugi 2000; Sinha and Labi 2007), different countries use different measures in transportation investment evaluation criteria. In Table 1 of the literature review section, five different nations' project evaluation criteria were identified. Of those, value of time is one actively utilized measure, with the U.S. using the annual wage rate based on working type for its valuation of time assessment.

Using this information, the difference in value of time for five route options can be calculated. First, the average wage rate of U.S. employees should be identified. According to the Bureau of Labor Statistics and other resources, the average hourly wage rate for all occupations in the U.S. in 2011 was $23.58 (United States Department of Labor 2012; YCharts 2012). The reports further divide average wage rate into separate occupation types, but as this study's main interest is in estimating the approximate value of time for each path option, the national average wage rate is used.

Another part of time valuation is based on ridership level. As can be seen in Table 44, value of time is based on each individual's average hourly rate. Therefore, without approximate passenger capacity for each path, value of time cannot be precisely assessed. The Korean HSR can carry up to 410 passengers in one-way operation (Maintenance data received from the sponsor for the year 2011). In addition, based on historic patterns, the minimum level of ridership is 10% and the average is around 60% (Based on personal conversation with the sponsor). Measurements for German HSR are similar. According to Chester and Horvath, the minimum occupancy of the German HSR in 2009 was 10% and the average was 63% (Chester and Horvath 2010).

Implementing the average wage rate and the above ridership information, Table 44 describes wage rate difference under different passenger loads. According to the result, route options in the study area can be expected to have a value of time ranging from $967 / hour to $9,668 / hour.

Table 44 Wage Rates under Different Passenger Capacity

Average Wage Rate	**Passenger Capacity**		
	Minimum Load (10%)	Average Load (60%)	Maximum Load (100%)
$23.58 / hr	41.0 persons	246.0 persons	410.0 persons
Total	**$966.78/hr**	**$5,800.68/hr**	**$9,667.80/hr**

Using these variances, each path's total wage per hour under the different passenger capacity can be assessed. Table 45 indicates each path's expected value of time under different passenger capacities. Because value of time is a measurement based on the length of each alternative, Path 5 consumes the most, whereas Paths 2 and 4 require the least economic value for time. The difference between Paths 5 and 2 (or Path 4) is about $505.95 / hour at the maximum capacity.

This measure is based on one-way operation per day with the total value of time differing based on number of operations that the proposed HSR will have. If we assume an HSR in the study area will conduct five roundtrips per day, the total value of time using the average capacity of Path 5 would be $48,204 ($4,820.37 x 2 x 5), and for Path 2 will be $45,168 ($4,516.80 x 2 x 5). In this case, the total difference between Path 2 and 5 will be $3,036 per day. In other words, implementing Path 2 or 4 instead of Path 5 will save a value of time approximately equivalent to $3,036 per day. If converted to an annual measure, the difference will be $1,108,027 per year. Finally, if calculated over the efficiency period, 20 to 50 years timespan, the difference will amount to about $22.1 million to $55.4 million in a 20-to-50-year time span.

Table 45 Hourly Wage Difference for Each Path Option

	Path1	Path2	Path3	Path4	Path5
Length	241.50km	233.60km	239.20km	233.60km	249.30km
Travel Time @300km/hr	0.81hr	0.78hr	0.80hr	0.78hr	0.83hr
Wage-Minimum Capacity	$778.26 /one-way trip	$752.80 /one-way trip	$770.85 /one-way trip	$752.80 /one-way trip	$803.39 /one-way trip
Wage-Average Capacity	$4,669.55 /one-way trip	$4,516.80 /one-way trip	$4,625.08 /one-way trip	$4,516.80 /one-way trip	$4,820.37 /one-way trip
Wage-Maximum Capacity	$7,782.58 /one-way trip	$7,527.99 /one-way trip	$7,708.46 /one-way trip	$7,527.99 /one-way trip	$8,033.94 /one-way trip

5.3.3 Summary of Operation Cost Estimate

As discussed above, the operational aspect of HSR consists of two parts: 1) variable and fixed cost, and 2) value of time. Table 46 summarizes the operation costs for each route alternative. Path 5 indicates the most costly option, whereas Paths 2 and 4 provide the least expensive alternatives. Because the value of time depends on the number of trains per day, the total value remains undetermined. However, this information is used to assess the total operation costs associated with each path option.

As briefly described, conventional practices on transportation project evaluation generally give weight to two aspects: construction and operation costs. In such cases, it would be reasonable to select the final path option based solely on those two cost elements. In this case, Path 2 would be the optimal route as it requires the smallest investment in construction and lowest annual operation costs (Tables 41 & 46).

As can be seen in Table 46, Path 5 requires around $18.4 million more than Paths 2 or 4 in operational costs with the average passenger loads. Paths 1 and 3 require $9.25 million and $6.59 million more than Paths 2 or 4. In this case, if Path 2 or 4 consumes environmental costs of more than $6.59 million/year, we will be able to say that Path 3 is more efficient with all things considered. Further, if Paths 2 or 4 requires environmental costs of more than $18.4 million/year, Path 5 may become a more feasible option despite its significant demand in maintenance.

Table 46 Operation Cost Summary

		Path1	Path2	Path3	Path4	Path5
Costs (1)	Variable Costs	$265.7million / year	$257.0million / year	$263.2million / year	$257.million / year	$274.3million / year
	Fixed Costs	$148.6million / year	$148.6million / year	$148.6million / year	$148.6million / year	$148.6million / year
	Total	$414.3million / year	$405.6million / year	$411.8million / year	$405.6million / year	$422.9million / year
Value of Time	Min. Capacity	$778.26 /one-way trip	$752.80 /one-way trip	$770.85 /one-way trip	$752.80 /one-way trip	$803.39 /one-way trip
	Average Capacity	$4,669.55 /one-way trip	$4,516.80 /one-way trip	$4,625.08 /one-way trip	$4,516.80 /one-way trip	$4,820.37 /one-way trip
	Max. Capacity	$7,782.58 /one-way trip	$7,527.99 /one-way trip	$7,708.46 /one-way trip	$7,527.99 /one-way trip	$8,033.94 /one-way trip
5 round trips a day for 1 year (2)	Min. Capacity	$2.84million / year	$2.75million / year	$2.81million / year	$2.75million / year	$2.93million / year
	Average Capacity	$17.04million / year	$16.49million / year	$16.88million / year	$16.49million / year	$17.59million / year
	Max. Capacity	$28.41million / year	$27.48million / year	$28.14million / year	$27.48million / year	$29.32million / year
Total (1) + (2)	Min. Capacity	$417.14million / year	$408.35million / year	$414.61million / year	$408.35million / year	$425.83million / year
	Difference	**+$8.79million / year**	-	**+$6.26million / year**	-	**+$17.48million / year**
	Average Capacity	$431.34million / year	$422.09million / year	$428.68million / year	$422.09million / year	$440.49million / year
	Difference	**+$9.25million / year**	-	**+$6.59million / year**	-	**+$18.40million / year**
	Max. Capacity	$442.71million / year	$433.08million / year	$439.94million / year	$433.08million / year	$452.22million / year
	Difference	**+$9.63million / year**	-	**+$6.86million / year**	-	**+$19.14million / year**

Another way to interpret this result is that we can expect more variances if a longer time span is considered because these measures are annual costs. As mentioned earlier, a typical efficiency period for a transportation project in the U.S. varies between 20 and 50 years. Hence, if annual environmental costs for Paths 5 or 3 are lower than those for 2 or 4, total costs will become more competitive within the same time span. To verify this hypothesis, environmental impact needs to be estimated as an opportunity cost.

5.4 Environmental Cost Estimate

In order to estimate the associated environmental costs for each path option, four different steps should be taken. First, land cover types within the study boundary need to be identified. To facilitate this analysis, some cover types will be aggregated to measure their values as one ecosystem feature. For example, forest in the study area is comprised of three types: deciduous, evergreen, and mixed forest. There are some studies that assign different economic values for each forest type, but more analyses are done at the aggregate level as forest is more measurable as a unified feature. Therefore, measurement of some land cover types, such as forest or wetland, will be aggregated.

The second step concerns finding relevant literature describing the values of each land cover type within the study area. As mentioned before, there are databases for valuation resources, a good example being the Environmental Valuation Reference Inventory (EVRI). This interactive website provides comprehensive summaries of recent valuation studies and allows searching and examination of each published article. Based on EVRI and other literature, a total of 51 articles are used to identify values of each land cover type in the study area. Some studies provide minimum and maximum values for land cover types, whereas others suggest an overall cost.

The third step involves calculating the number of pixels for each land cover for the route options. As briefly mentioned, each alternative consumes different amounts of natural assets. To precisely gauge the extent of ecosystem features consumed, the number of pixels in each land cover type is calculated by corresponding route paths. Because a cell is 30 x 30m in its size, obtaining the number of pixels for a single land cover type will give an estimate of the areas of environmental features consumed by the route. In addition, most valuation studies calculate environmental costs in area (acre or hectare) per year. Therefore, calculating the total area for the corresponding land cover type gives an annual estimate of the selected land cover types.

The last step is calculating the economic value of land cover types damaged by each route option over the same efficiency periods. As the values are given in an annual measure, the same time period for a transportation investment in the U.S., 20-to-50 years, will be applied to calculate the total economic values of ecosystem features. As seen before, if Paths 5 and 3 can make up a significant portion of construction and operation costs by consuming less in environmental externalities, they could possibly become more economically efficient route options.

5.4.1 Land Cover Types in the Study Area

Based on the land cover datasets from the United States Geological Survey (USGS), there are 15 land cover types in the study area. Table 47 and Figure 36 summarize the result with the suggested aggregated measures. Among those, land cover type 22 (Developed with low intensity) through 24 (Developed with high intensity) will not be included as a part of environmental costs because they are more closely related to man-made environment rather than natural assets. Only Open Space will be accounted for in the valuation as it has high relevance to the natural environment. Furthermore, as mentioned earlier, some land cover types will be aggregated to facilitate the analysis and assist the search for relevant literature works. Different forest types will be measured as one forest, and the same logic applies to the wetlands.

Table 47 Land Cover Types in the Study Area

No.	Land Cover Type	New (aggregated) Measures
11	Open Water	Open Water
21	Developed, Open Space	Urban Open Space
22	Developed, Low Intensity	N/A
23	Developed, Medium Intensity	
24	Developed, High Intensity	
31	Barren Land	
41	Deciduous Forest	Forest
42	Evergreen Forest	
43	Mixed Forest	
52	Shrub / Scrub	Shrub
71	Herbaceous	Herbaceous
81	Hay / Pasture	Pasture
82	Crops	Crop
90	Woody Wetlands	Wetland
95	Emergent Herbaceous Wetlands	

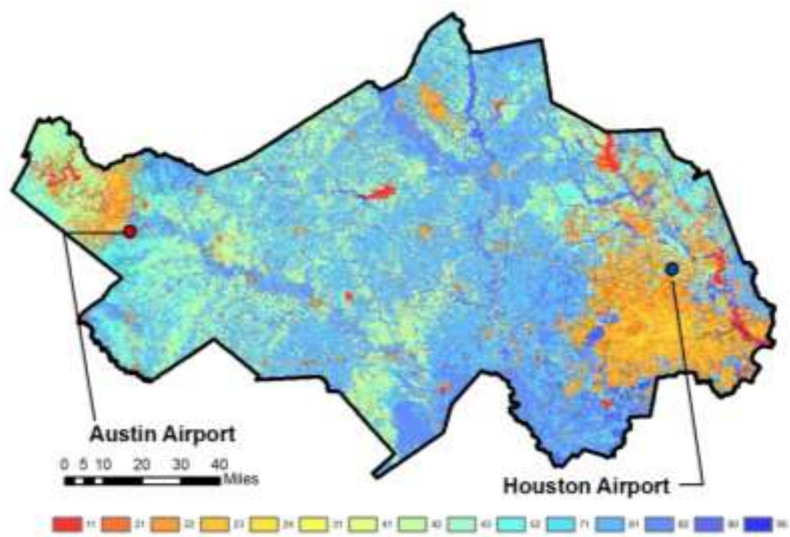


Figure 36 Land Cover Types in the Study Area

5.4.2 Value Transfer Literature

Using the EVRI, Natural Capital Project (NCP) databases, and literature reviews, 51 articles relevant to the abovementioned land cover types and the economic values associated with their ecosystem services are identified. As mentioned previously, ecosystem services will only be measured in relevance to human activities and man-made environments. There is a multitude of ecosystem services connected to nature but irrelevant to direct human activities, and such services should not be underestimated. However, as ecosystem features and their services have no direct markets to be traded in monetary terms, it is hard to measure values that are not directly associated with the human environment. To this extent, ecosystem services that are only related to human activities and man-made environment will be assessed in economic terms.

Table 48 summarizes the number of references cited in this study. As can be seen, all land cover types are assessed with seven different services they provide to human activities or to the man-made environment. Studies assessing the overall value of land cover types are also included. Forest and Wetland are the most widely studied features, whereas Pasture is the least analyzed. Further, Water Regulation and Recreation values are the most cited services, and Pollination and Soil Formation are the least studied ones.

Table 48 Number of References Cited for Value Transfer

	Overall Estimate	Climate Regulation	Water Supply & Regulation	Recreation & Aesthetic	Habitat Refuge	Pollination	Soil Formation & Control	**Total**
Open Water	2	-	2	2	1	-	-	**7**
Urban Open Space	1	4	2	2	-	-	-	**9**
Forest	3	6	3	4	9	2	-	**27**
Shrub	-	2	-	9	4	-	-	**15**
Herbac-eous	1	2	3	1	1	1	2	**11**
Pasture	2	-	-	1	-	-	1	**4**
Crop	3	3	1	3	1	-	1	**12**
Wetland	3	1	10	8	5	-	-	**27**
River/Lake	-	-	6	11	2	-	-	**19**
Total	**15**	**18**	**27**	**41**	**23**	**3**	**4**	**131**

Table 49 shows detailed information on each land cover type and its corresponding services, cited literature, and assessed economic values. As can be seen, there are studies that suggests an overall value of the services provided by a land cover type, while others write in terms of minimum and maximum available values.

Referenced studies used different dollar years, but all represent dollars per acre per year. In other words, if the area of each land cover type is at hand, multiplying the values by the total area of a particular land cover type will give the outline of economic values for the ecosystem services that a land cover provides.

Table 49 Detailed Information of Each Reference for Value Transfer

Land Cover Types & Their Type of Services			No. of Studies	References	Dollar Year	2012 Values ($ / acre / year)		
						Min	Max	Single Value
Open Water	Overall Estimate		2	Kauffman 2011	2010			2,062.76
				Troy & Wilson 2006	2004			21,817.25
	Detailed Estimate	Water Supply & Regulation	2	Batker, De La Torre et al. 2010	2004	33.61	876.72	
				Quenani-Petrela, Noel et al. 2007	2007			3,066.71
		Recreation & Aesthetic	2	Batker, De La Torre et al. 2010	2004	1.76	1,994.30	
				Quenani-Petrela, Noel et al. 2007	2007			507.08
		Habitat Refuge	1	Ingraham & Foster 2008	2004			20.76
Urban Open Space	Overall Estimate		1	Wilson, Troy et al. 2008	2001	3,523.68	5,455.39	
	Detailed Estimate	Climate Regulation	4	McPherson, Scott et al. 1998	2006			30.83
				McPherson 1992	2006	201.68	1,006.01	
				Batker, De La Torre et al. 2010	2004	30.65	1,000.01	
				Quenani-Petrela, Noel et al. 2007	2007			410.46
		Recreation & Aesthetic	2	Tyrvainen 2001	2004	1,441.86	4,226.69	
				Quenani-Petrela, Noel et al. 2007	2007			2,350.47
		Water Supply & Regulation	2	McPherson 1992	2006			196.52
				Quenani-Petrela, Noel et al. 2007	2007			6.87
Forest	Overall Estimate		3	Kauffman 2011	2010			2,096.68
				Troy & Wilson 2006	2004			5,504.81
				Wilson, Troy et al. 2004	2001	530.65	2,614.45	
	Detailed Estimate	Climate Regulation	6	Batker, De La Torre et al. 2010	2004	12.90	16.26	
				Batker, De La Torre et al. 2009	2006	185.53	611.46	

(**Table 49** Continued)

Land Cover Types & Their Type of Services			No. of Studies	References	Dollar Year	2012 Values ($ / acre / year) Min	2012 Values ($ / acre / year) Max	2012 Values ($ / acre / year) Single Value
				Batker, Barclay et al. 2005	2001	265.93	690.37	
				Quenani-Petrela, Noel et al. 2007	2007			36.80
				Herrera et al. 2004	2001	1,569.34	7,061.87	
				Earth Economics 2010	2006	31.54	716.83	
		Recreation & Aesthetic	4	Batker, De La Torre et al. 2010	2004	0.18	662.97	
				Batker, Barclay et al. 2005	2001	151.96	2,690.74	
				Quenani-Petrela, Noel et al. 2007	2007			225.75
				Herrera et al. 2004	2001	34.23	2,986.62	
		Habitat Refuge	9	Haener & Adamowicz 2000	2006	1.41	9.73	
				Shafer, Carline et al. 1993	2006			3.43
				Kenyon & Nevin 2001	2006			575.28
				Batker, De La Torre et al. 2010	2004	1.28	2,632.77	
				Earth Economics 2010	2006	310.33	520.46	
				Batker, Barclay et al. 2005	2001	706.09	2,152.33	
				Quenani-Petrela, Noel et al. 2007	2007			143.00
				Herrera et al. 2004	2001	7.90	54.37	
				Ingraham & Foster 2008	2004			36.11
		Water Supply & Regulation	3	Loomis 2002	2006			11.05
				Batker, Barclay et al. 2005	2001	1,412.18	10,738.07	
				Herrera et al. 2004	2001			42.46
		Pollination	2	Hougner, Colding et al. 2006	2006	72.42	325.24	
				Batker, Barclay et al. 2005	2001	19.65	35.37	
Shrub/Scrub	Detailed Estimate	Climate Regulation	2	Batker, De La Torre et al. 2009	2006			78.78
				Earth Economics 2010	2006	7.13	71.65	
		Habitat Refuge	4	Shafer, Carline et al. 1993	2006			3.43
				Kenyon & Nevin 2001	2006			575.28
				Haener & Adamowicz 2000	2006			0.71
				Ingraham & Foster 2008	2004			484.63
		Recreation & Aesthetic	9	Willis 1991	2006	11.25	20.52	
				Willis & Garrod 1991	2006			4.73
				Prince & Ahmed 1989	2006	1.71	2.19	
				Maxwell 1994	2006			13.55
				Haener & Adamowicz 2000	2006			0.23
				Boxall, McFarlane et al 1996	2006			0.21
				Bennett 1995	2006			194.50

(**Table 49** Continued)

Land Cover Types & Their Type of Services			No. of Studies	References	Dollar Year	2012 Values ($ / acre / year) Min	Max	Single Value
				Bishop 1992	2006	654.36	733.48	
				Shafer, Carline et al. 1993	2006			619.84
Grassland/ Herbaceous	Overall Estimate		1	Troy & Wilson 2006	2004			355.73
	Detailed Estimate	Climate Regulation	2	Costanza et al 1997	2006			4.43
				Herrera et al. 2004	2001			26.66
		Soil Formation	2	Costanza et al 1997	2006			18.99
				Herrera 2004	2001			3.81
		Water Supply & Regulation	3	Costanza et al 1997	2006			1.90
				Herrera et al. 2004	2001			342.43
				Pimentel, Wilson et al. 1997	2006			55.10
		Pollination	1	Pimentel, Wilson et al. 1997	2006			15.84
		Habitat Refuge	1	Ingraham & Foster 2008	2004			5.90
		Recreation & Aesthetic	1	Herrera et al. 2004	2001			7.60
Pasture	Overall Estimate		2	Troy & Wilson 2006	2001			11,044.90
				Wilson, Troy et al. 2004	2001			1,805.52
	Detailed Estimate	Soil Formation	1	Pimentel, Wilson et al. 1997	2006			7.15
		Recreation & Aesthetic	1	Boxall, McFarlane et al 1996	2006			0.03
Crop(land)	Overall Estimate		3	Kauffman 2011	2010			3,125.94
				Troy & Wilson 2006	2004			6,608.18
				Wilson, Troy et al. 2004	2001			1,815.23
	Detailed Estimate	Recreation & Aesthetic	3	Bergstrom et al. 1985	2010			29.15
				Batker, De La Torre et al. 2010	2004			31.44
				Quenani-Petrela, Noel et al. 2007	2007			924.67
		Pollination	4	Southwick & Southwick 1992	2009			2.59
				Robinson et al. 1989	2009			13.07
				Batker, De La Torre et al. 2010	2004	2.75	13.83	
				Quenani-Petrela, Noel et al. 2007	2007			10.06
		Habitat Refuge	1	Quenani-Petrela, Noel et al. 2007	2007			15.65
		Water Regulation	1	Quenani-Petrela, Noel et al. 2007	2007			129.44
		Soil Formation	1	Quenani-Petrela, Noel et al. 2007	2007			7.11
Wetland	Overall Estimate		3	Kauffman 2011	2010			14,438.26
				Troy & Wilson 2006	2001			27,430.98
				Wilson, Troy et al. 2004	2001	10,059.79	41,601.39	
	Detailed Estimate	Climate Regulation	1	Earth Economics 2010	2006	30.83	307.66	
		Water Supply & Regulation	10	Lant & Tobin 1989	2006			209.56
				Pate & Loomis 1997	2006			4,138.02
				Lant & Roberts 1990	2006			0.39
				Hayes, Tyrrell et al. 1992	2006	1,481.00	2,302.13	
				Creel & Loomis 1992	2006			624.05

(**Table 49** Continued)

Land Cover Types & Their Type of Services			No. of Studies	References	Dollar Year	2012 Values ($ / acre / year) Min	Max	Single Value
				Batker, De La Torre et al. 2010	2004	7,474.74	11,008.01	
				Thibodeau 1981	2006			7,311.36
				Quenani-Petrela, Noel et al. 2007	2007			564.18
				Herrera et al. 2004	2001			17.15
		Recreation & Aesthetic	8	Thibodeau 1981	2006	36.19	115.78	
				Doss & Taff 1996	2006			4,816.07
				Batker, De La Torre et al. 2010	2004	32.71	4,809.24	
				Whitehead 1990	2006	1,201.36	2,415.45	
				Mahan & Polasky et al. 2000	2006			39.96
				Hayes, Tyrrell et al. 1992	2006	1,394.77	2,665.80	
				Herrera et al. 2004	2001			2,808.39
				Quenani-Petrela, Noel et al. 2007	2007			2,772.57
		Habitat Refuge	5	Batker, De La Torre et al. 2010	2004			6.15
				Herrera et al. 2004	2001	4,970.04	144,635.79	
				Ingraham & Foster 2008	2004			1,039.00
				Earth Economics 2010	2006	67.72	310.40	
				Quenani-Petrela, Noel et al. 2007	2007			6.15
River/Lake	Detailed Estimate	Water Supply & Regulation	6	Ribaudo & Epp 1984	2006			969.96
				Piper 1997	2006			37.19
				Henry & Ley et al. 1988	2006			493.70
				Croke & Fabian et al. 1987	2006			650.80
				Bouwes & Scheider 1979	2006			710.08
				Batker, Barclay et al. 2005	2001	24.38	178.71	
		Habitat Refuge	2	Earth Economics 2010	2006	67.72	310.40	
				Batker, Barclay et al. 2005	2001	55.05	162.73	
		Recreation & Aesthetic	11	Young & Onstad 1989	2006			94.13
				Ward & Roach et al. 1996	2006	23.55	2,206.40	
				Shafer, Carline et al. 1993	2006			2,012.95
				Piper 1997	2006			276.23
				Patrick & Fletcher et al. 1991	2006	1.94	29.39	
				Kreutzwiser 1981	2006			208.47
				Kealy 1986	2006			14.87
				Cordell & Bergstrom 1993	2006	155.68	326.36	
				Burt & Brewer 1971	2006			531.09
				Loomis 2002	2006	12,800.65	22,653.85	
				Batker, Barclay et al. 2005	2001	7.09	125.96	

As noted, all the studies have different dollar years. To convert the values with proper inflation rate, the Consumer Price Index (CPI) inflation calculator was used (Bureau of Labor Statistics 2012). In addition, because each land cover has a wide range of associated economic values for its ecosystem services, deciding a standard value for each cover type is necessary.

Some covers have a significant range of economic values. For instance, Batker et al. identified the minimum value of open water for providing water regulation service as \$1.44 per acre per year, and the maximum as \$1,634.67. The maximum value is 1,000 times greater than the minimum, and this should not be considered a reliable measure as the variance is too high. It would be more logical and reasonable to use the median values for each cover type. Table 50 indicates the median, average, minimum, and maximum values for each land cover type. Economic values of environmental features will first be assessed with the median values for each land cover type.

Table 50 Median and Average Values (\$/acre/year) for Each Land Cover Type

Land Cover Types	Median	Mean	Minimum	Maximum
Open Water	\$876.72	\$3,375.66	\$1.76	\$21,817.25
Urban Open	\$1,000.01	\$1,529.32	\$6.87	\$5,455.39
Forest	\$245.84	\$1,102.47	\$0.18	\$10,738.07
Shrub	\$13.55	\$183.06	\$0.21	\$733.48
Herbaceous	\$15.84	\$76.22	\$1.90	\$355.73
Pasture	\$906.34	\$3,214.40	\$0.03	\$11,044.90
Crop	\$22.4	\$909.22	\$2.59	\$6,608.18
Wetland	\$1,437.89	\$8,420.64	\$0.39	\$144,635.79
River / Lake	\$178.71	\$1,671.46	\$1.94	\$22,653.85

5.4.3 Number of Pixels and Total Area Consumed by Each Land Cover Type

Acquiring the number of pixels for each path's land cover types allows calculation of the amount of ecosystem services consumed by the route. Multiplying the median values in

Table 50 will show basic economic values of each service that the land cover provides. Cell counts and the amount of areas consumed by each route option are depicted in Table 51. As the developed lands are not a consideration in the environmental cost calculation, their cell counts and areas are not included. As can be seen in Table 51, Path 5 consumes the least amount (acres) of environmental land covers, whereas Path 1 expends the most. As Paths 4 and 5 are intended to avoid the areas where water and green resources are predominate, the route should cross relatively fewer areas of the land cover types such as Shrubs and Forest.

In the previous sections, Paths 2 and 4 turned out to be the most efficient route alternatives in terms of operation costs. If the environmental costs for Paths 2 and 4 exceed those of Path 5, then the overall costs of Path 5 may become a more economically feasible option.

5.4.4 Economic Values by Land Cover Types

By using the median values in Table 50 and the total areas of land cover types for each path option in Table 51, the overall economic values of environmental features for each route alternative can be assessed. As the median values are in 2012 dollars per acre per year, simply multiplying the values by the acres of each land cover type for each path option will give the estimates. Table 52 illustrates the overall economic values of environmental features that each route consumes.

As evinced in Table 52, Path 5 consumes the smallest economic value of environmental systems, whereas Path 2 destructs the most when using a median value for environmental services. Path 2 requires approximately \$5.3 million / year for its ecosystem services damaged by HSR operation, and Path 5 requires \$4.5 million / year. If this cost difference is considered in terms of a transportation project's efficient period, a 20-to-50 year time span, then the difference between Paths 2 and 5 would become \$15.9 million to \$39.9 million.

Table 51 Cell Count & Area Calculation of Land Cover Types for Each Path

Path & Quantity		Open Water	Urban Open	Forest	Shrub	Herbaceous	Pasture	Crop	Wetland	Total Area
Path1	Cell	369	3,472	7,823	4,485	2,622	15,236	1,701	2,347	**8,463.05 acres**
	m^2	332,100	3,124,800	7,040,700	4,036,500	2,359,800	13,712,400	1,530,900	2,112,300	
	Acre	**82.06**	**772.14**	**1,739.76**	**997.42**	**583.11**	**3,388.33**	**378.29**	**521.95**	
Path2	Cell	310	2,458	6,943	3,703	2,078	17,869	1,444	2,123	**8,212.42 acres**
	m^2	279,000	2,212,200	6,248,700	3,332,700	1,870,200	16,082,100	1,299,600	1,910,700	
	Acre	**68.94**	**546.63**	**1,544.05**	**823.51**	**462.13**	**3,973.89**	**321.13**	**472.13**	
Path3	Cell	147	3,671	6,464	3,717	2,010	16,126	1,322	1,391	**7,749.85 acres**
	m^2	132,300	3,303,900	5,817,600	3,345,300	1,809,000	14,513,400	1,189,800	1,251,900	
	Acre	**32.69**	**816.39**	**1,437.53**	**826.62**	**447.00**	**3,586.26**	**294**	**309.34**	
Path4	Cell	183	5,148	4,862	3,436	1,978	16,796	1,381	550	**7,635.54 acres**
	m^2	164,700	4,633,200	4,375,800	3,092,400	1,780,200	15,116,400	1,242,900	495,000	
	Acre	**40.7**	**1,144.86**	**1,081.26**	**764.13**	**439.89**	**3,735.26**	**307.12**	**122.31**	
Path5	Cell	582	5,127	3,540	3,919	1,365	12,446	826	1,633	**6,546.72 acres**
	m^2	523,800	4,614,300	3,186,000	3,527,100	1,228,500	11,201,400	743,400	1,469,700	
	Acre	**129.43**	**1,140.19**	**787.26**	**871.55**	**303.56**	**2,767.87**	**183.69**	**363.16**	

Table 52 Environmental Cost Estimate ($/year) for Each Path Using Median Values

Path & Quantity		Open Water	Urban Open	Forest	Shrub	Herbaceous	Pasture	Crop	Wetland	Total Value
Median Values		**$876.72**	**$1,000.01**	**$245.84**	**$13.55**	**$15.84**	**$906.34**	**$22.40**	**$1,437.89**	
Path1	Acre	82.06	772.14	1,739.76	997.42	583.11	3,388.33	378.29	521.95	**$5,124,506**
	Value	**$71,945**	**$772,146**	**$427,702**	**$13,515**	**$9,236**	**$3,070,983**	**$8,474**	**$750,506**	
Path2	Acre	68.94	546.63	1,544.05	823.51	462.13	3,973.89	321.13	472.13	**$5,292,908**
	Value	**$60,441**	**$546,640**	**$379,590**	**$11,158**	**$7,320**	**$3,601,693**	**$7,193**	**$678,871**	
Path3	Acre	32.69	816.39	1,437.53	826.62	447.00	3,586.26	294.00	309.34	**$4,918,507**
	Value	**$28,661**	**$816,402**	**$353,402**	**$11,201**	**$7,081**	**$3,250,372**	**$6,586**	**$444,803**	
Path4	Acre	40.70	1,144.86	1,081.26	764.13	439.89	3,735.26	307.12	122.31	**$5,031,866**
	Value	**$35,680**	**$1,144,875**	**$265,817**	**$10,354**	**$6,968**	**$3,385,418**	**$6,879**	**$175,875**	
Path5	Acre	129.43	1,140.19	787.26	871.55	303.56	2,767.87	183.69	363.16	**$4,498,768**
	Value	**$113,475**	**$1,140,205**	**$193,540**	**$11,809**	**$4,808**	**$2,508,628**	**$4,115**	**$522,188**	

As can be seen, Path 1 costs about $5.12 million per year, and Paths 3 and 4 consume about $4.92 million and $5.03 million in annual environmental costs. Paths 3 and 5 were the most efficient routes in terms of environmental externalities, while Paths 1 and 2 became the two most costly options. This is an expected result as both Paths 1 and 2 are designed more for human environments, such as population density or land uses, than natural assets.

5.4.5 Economic Values of Hydrologic Units

In Table 49, nine different environmental features' valuation references have been identified; Tables 51 and 52 only include eight types as the Lake and River element has been dropped from the valuation calculation result. The main reason for this is because lakes and rivers are not defined in the land cover datasets provided by the U.S.G.S. (U.S. Geological Survey 2010). Therefore, these elements should be dealt with a different matter. One of input variables, for instance, specifically describes about Lake and River.

As defined in Table 28, the Hydrologic Unit variable consists of five classifications, and the last two indicate large streams and lakes or reservoirs. This information can easily be accessed through each path's cell attributes, and their amount of area would also be quantified. Identified in Table 32, each path consumes a different area of Major Rivers, and Lakes and Reservoirs, classification scores of 4 and 5 respectively. Table 53 summarizes the result only with the two last classifications for each route. It indicates that Path 2 consumes the greatest area for these two classifications, and Path 4 requires the least.

Table 53 Area of the Major Hydrologic Units Consumed by Each Path in Acre

Hydrologic Units	Path 1	Path 2	Path 3	Path 4	Path 5
Major Rivers	**45**	24	25	**16**	20
Lake and Reservoirs	10	36	**6**	8	**22**
Total	55	**60**	31	**24**	42

The median economic value of lakes or rivers based on the references in Table 50 is $178.71 / acre / year. Using this value and the acreage information in Table 53, total economic values of lakes or rivers consumed by each route is calculated; Table 54 summarizes the result. As can be seen, Path 2 consumes the greatest value, whereas Path 4 consumes the least. Although the costs of these hydrologic units compared to the other land cover types are relatively minimal, their cost difference is notable among the route options. Similar to the previous environmental costs result, Paths 1 and 2 indicate the highest costs in hydrologic variables as well, and Paths 3, 4, and 5 show reasonably low estimates as they all are designed to avoid environmental variables.

Table 54 Economic Values of Hydrologic Units Consumed by Each Path

Acreage & Cost	Path 1	Path 2	Path 3	Path 4	Path 5
Acreage of Lake or Rivers	55 acres	**60 acres**	31 acres	**24 acres**	42 acres
Median Economic Values of Lake or River ($/acre)	$178.71	$178.71	$178.71	$178.71	$178.71
Annual Environmental Costs for Lake & River	$9,829	**$10,723**	$5,540	**$4,289**	$7,506

5.4.6 Environmental Cost Estimates with the Median Values

Using the values in Table 52 and Table 54, total environmental cost estimates for each path can be assessed. Table 55 summarizes the result. Path 2 is the most environmentally inefficient route and Path 5 is the most beneficial one. By constructing Path 2, we would expect to lose about $5.3 million worth of annual environmental values. On the contrary, building Path 5 would cost about $4.51 million annually in environmental losses. It is about 20% difference from the highest to lowest route options. Interpreting this in a different way, constructing Path 2 would destroy about $0.8 million of environmental features within the study boundary per year more than doing the same with Path 5. Path 1 indicates an annual environmental cost of $5.1 million, and Paths 3 and 4 show $4.9 million / year and $5.04 million / year, respectively.

Table 55 Environmental Cost by Feature Type Using the Median Values ($/year)

Land Cover Types (unit cost)	Path 1	Path 2	Path 3	Path 4	Path 5
Open Water ($876.72)	$71,945	$60,442	$28,661	$35,680	$113,475
Urban Open ($1,000.01)	$772,146	$546,640	$816,402	$1,144,875	$1,140,205
Forest ($245.84)	$427,701.85	$379,590.18	$353,402.12	$265,817.00	$193,540.15
Shrub ($13.55)	$13,515	$11,159	$11,201	$10,354	$11,809
Herbaceous ($15.84)	$9,236	$7,320	$7,080	$6,968	$4,808
Pasture ($906.34)	$3,070,983	$3,601,693	$3,250,372	$3,385,418	$2,508,628
Crop ($22.40)	$8,474	$7,193	$6,586	$6,879	$4,115
Wetland ($1,437.89)	$750,506	$678,871	$444,803	$175,875	$522,188
River / Lake ($178.71)	$9,829	$10,723	$5,540	$4,289	$7,506
Total	**$5,134,335**	**$5,303,630**	**$4,924,047**	**$5,036,155**	**$4,506,274**

5.4.7 Environmental Cost Estimates with the Other Values

In Section 5.4.2, environmental valuation references are summarized into four values: median, average, minimum, and maximum. The main reason for using the median values was to avoid any effect from abnormal outliers, and to use the references in a more valid manner. Using the median values, each route option's environmental cost estimates were calculated during the previous sections. Based on the results, it would be helpful to understand more thoroughly on externalities by calculating the environmental costs with the mean values as well.

Table 56 illustrates the environmental costs associated with each path alternative using the average values. As can be seen, all the values are about 3.5 times greater than the corresponding values in Table 55. Using this outcome, implementing Path 2 would require $20.1 million per year of environmental costs, and Path 5 would consume about $15.42 million per year of environmental costs, a difference of $4.7 million per year. Path 1 indicates an annual environmental value of $19.33 million, and Paths 4 and 5 show $17.58 million and $16.61 million per year, respectively.

Table 56 Environmental Cost Summary Using the Average Values ($/year)

Land Cover Types (unit cost)	Path1	Path2	Path3	Path4	Path5
Open Water ($3,375.66)	$277,013	$232,721	$110,355	$137,381	$436,915
Urban Open ($1,529.32)	$1,180,846	$835,979	$1,248,527	$1,750,863	$1,743,721
Forest ($1,102.47)	$1,918,029	$1,702,273	$1,584,833	$1,192,057	$867,931
Shrub ($183.06)	$182,588	$150,752	$151,322	$139,882	$159,545
Herbaceous ($76.22)	$44,444	$35,223	$34,071	$33,528	$23,137
Pasture ($3,241.40)	$10,891,461	$12,773,662	$11,527,678	$12,006,628	$8,897,028
Crop ($909.22)	$343,945	$291,979	$267,310	$279,240	$167,018
Wetland ($8,420.64)	$4,395,147	$3,975,637	$2,604,879	$1,029,966	$3,058,064
River / Lake ($1,671.46)	$91,930	$100,288	$51,815	$40,115	$70,201
Total	**$19,325,404**	**$20,098,514**	**$17,580,789**	**$16,609,660**	**$15,423,562**

Table 57 indicates the environmental values of each path with the maximum possible unit costs based on the references. Unlike the previous results, Path 4 came out to be the most efficient one because the unit cost for wetland is much pricier than the others and the difference in wetland consumption creates significant changes in the total costs. The least efficient option is Path 1 and the difference between the two is about $61.3 million per year. Path 5, the most environmentally feasible option in the previous analyses, consumes about $103.51 million annually with the maximum environmental costs, and Paths 2 and 3 require about $137.49 million and $108.37 million per year for their environmental costs, respectively.

Table 58 is based on the minimum possible environmental values for each path alternative. This one is also quite different from any of the previous results because Path 4 results in the greatest cost and path 2 the lowest. Unlike the result of calculation using the maximum costs, the unit cost of Urban Open Space seems to be the most valuable environmental feature, and its amount consumed by each route largely drives the total costs.

Table 57 Environmental Cost Summary Using the Maximum Values ($/year)

Land Cover Types (unit cost)	Path1	Path2	Path3	Path4	Path5
Open Water ($21,817.25)	$1,790,365	$1,504,101	$713,235	$887,905	$2,823,828
Urban Open ($5,455.39)	$4,212,314	$2,982,105	$4,453,746	$6,245,678	$6,220,200
Forest ($10,738.07)	$18,681,632	$16,580,157	$15,436,287	$11,610,648	$8,453,659
Shrub ($733.48)	$731,587	$604,028	$606,312	$560,476	$639,262
Herbaceous ($355.73)	$207,429	$164,392	$159,013	$156,481	$107,986
Pasture ($11,044.90)	$37,423,811	$43,891,184	$39,609,896	$41,255,600	$30,570,803
Crop ($6,608.18)	$2,499,778	$2,122,093	$1,942,802	$2,029,508	$1,213,884
Wetland ($144,635.79)	$75,492,554	$62,286,896	$44,742,285	$17,691,054	$52,526,349
River / Lake ($22,653.85)	$1,245,962	$1,359,231	$702,269	$543,692	$951,462
Total	**$142,285,431**	**$137,494,186**	**$108,365,844**	**$80,981,042**	**$103,507,433**

Table 58 Environmental Cost Summary Using the Minimum Values ($/year)

Land Cover Types (unit cost)	Path1	Path2	Path3	Path4	Path5
Open Water ($1.76)	$144	$121	$58	$72	$228
Urban Open ($6.87)	$5,305	$3,755	$5,609	$7,865	$7,833
Forest ($0.18)	$313	$278	$259	$195	$142
Shrub ($0.21)	$209	$173	$174	$160	$183
Herbaceous ($1.90)	$1,108	$878	$849	$836	$577
Pasture ($0.03)	$102	$119	$108	$112	$83
Crop ($2.59)	$980	$832	$762	$795	$476
Wetland ($0.39)	$204	$184	$121	$48	$142
River / Lake ($1.94)	$107	$116	$60	$47	$82
Total	**$8,471**	**$6,457**	**$7,998**	**$10,130**	**$9,744**

5.5 Total Cost Estimate

With the given cost information from the previous steps, total costs are calculated. This calculation process consists of two parts. First, each route's annual cost is determined. Doing so gives a basic outline of each path's consumption of construction, operation, and environmental costs. After that, the annual estimate is assessed with the same efficiency terms. The typical return-on-investment periods in the U.S., a 20-to-50-year time span will be used for all alternatives to articulate the difference in a longitudinal perspective.

5.5.1 Annual Total Costs for Each Path

In Section 5.4, four aspects of environmental costs are estimated. Of those, only the median and average values will be used to calculate the total costs for the reason that as shown in the previous section, the environmental costs using the maximum and minimum costs give two completely different results. In addition, as briefly mentioned previously, the variance among land covers for their maximum and minimum values shifts significantly and it is hard to perceive maximum and minimum values as a valid measure. Therefore, using the median and average values will draw a more reliable conclusion for total cost analysis.

Table 59 illustrates the three cost components: construction, operation, and environmental for each path option. Although environmental cost is included, Path 5 still proves to be the priciest option. Paths 2 and 4 rank as the most efficient ones; when using the median value Path 2 is the most efficient, while using the average value Path 4 becomes most efficient. The difference between Paths 2 and 5 is around \$769 million, while the difference between Paths 2 and 4 is about \$3.3 million. The main reason can be traced to the differences in construction and operation costs. Compared to Path 2, Path 5 requires approximately \$751.5 million more in construction costs and about \$18.4 million more in operation costs. Of the total difference in \$769 million, about 97% is due to the large gap in construction costs.

Table 59 Summary of Total Cost Analysis (* indicates annual measure)

Cost Elements			PATH01	PATH02	PATH03	PATH04	PATH05
Construction Costs							
Civil	Normal Soil	(Unit Cost)	62.4km	55km	76.4km	55.9km	55.7km
		$9,096,989 / km	$567,288,234	$499,788,576	$694,646,080	$508,521,685	$506,338,408
	Soft Soil	(Unit Cost)	179.1km	178.7km	162.8km	177.7km	193.6km
		$11,761,764 / km	$2,107,002,403	$2,101,356,756	$1,915,285,650	$2,090,065,463	$2,277,547,981
Bridge	Normal Bridge	(Unit Cost)	2.5km	1.4km	1.6km	0.9km	4.4km
		$27,842,300 / km	$68,213,635	$38,700,797	$43,712,411	$24,222,801	$122,784,543
	Over Bridge	(Unit Cost)	4.3 km	2.6 km	4.7 km	8.3 km	15.9km
		$3,124,218 / km	$13,277,927	$8,247,936	$14,590,098	$25,806,041	$49,706,308
Hardware	Other Hardware	(Unit Cost)	241.5 km	233.6 km	239.2 km	233.6 km	249.3 km
		$9,556,429 / km	$2,307,877,604	$2,232,381,814	$2,285,897,817	$2,232,381,814	$2,382,417,750
Software		$5,692,503 / km	$1,374,739,475	$1,329,768,701	$1,361,646,718	$1,329,768,701	$1,419,140,998
Land Acquisition Cost			$37,171,042	$37,751,851	$36,750,004	$40,759,567	$241,517,295
Total			$6,475,570,319	$6,247,996,431	$6,352,528,777	$6,251,526,072	$6,999,453,283
***Operation Costs**							
Variable Costs		(Unit Cost)	241.5 km	233.6 km	239.2 km	233.6 km	249.3 km
		$1,100,203 / km	$265,698,952	$257,007,351	$263,168,486	$257,007,351	$274,280,533
Fixed Costs		$148,582,896	$148,582,896				
Value of Time with average capacity		(Unit Cost)	1,825 trips per year				
		60% average load	$17,043,848	$16,486,306	$16,881,526	$16,486,306	$17,594,333
Total			$431,325,696	$422,076,553	$428,632,908	$422,076,553	$440,457,762
***Environmental Costs**							
Using Median values			$5,134,335	$5,303,630	$4,924,047	$5,036,155	$4,506,274
Using Average values			$19,325,404	$20,098,514	$17,580,789	$16,609,660	$15,426,562
Total Cost w/ Median Environmental Costs			$6,912,030,350	**$6,675,376,614**	$6,786,085,732	$6,678,638,780	**$7,444,417,319**
Difference			+$236,653,736	-	+$110,709,118	**+$3,262,166**	**+$769,040,705**
Total Cost w/ Average Environmental Costs			$6,926,221,419	**$6,690,171,497**	$6,798,742,474	$6,690,212,284	**$7,455,337,606**
Difference			+$236,049,922	-	+$108,570,977	**+$40,787**	**+$765,166,109**

According to the analysis result, Path 5 shows the highest total cost because it requires the most investment in construction, about $7 billion. This number comprises about 94% of the total cost. Using the median values, the environmental cost consists of about 0.08% of the total cost. Using the average value, it goes up to 0.28%. Since construction cost is essentially closer to a one-time investment, total costs in terms of project efficiency (construction costs exclusive) may change over time. Therefore, total costs in terms of 20-to-50-year time frame will be calculated as the following step.

5.5.2 Total Cost with Project Efficiency

As mentioned earlier in the literature review, the typical return-on-investment period for transportation investment project in the U.S. is 20 to 50 years (Hayashi and Morisugi 2000; Lee 2000; Morisugi 2000). Using this standard, each path's total cost in terms of efficiency is calculated with the operation and environmental costs, known as the recurring costs.

In some literature, lost service of ecosystem features is defined in two ways: 1) ecosystem with permanent injury, and 2) ecosystem with natural recovery (Herrera Environmental Consultants Inc., Northern Economics Inc. et al. 2004; Wilson, Troy et al. 2004; Wilson and Hoehn 2006). The former concerns the service lost (due to any kind of human activities) that will probably never be restored making the injuries are permanent. The latter describes the features damaged by human activities that recover with natural elasticity. In the latter case, lost ecosystem features will fully bounce back to their previous condition at some point in future.

A more detailed distinction is explained in the literature review section. Figure 2 of Section 2.3 graphically illustrates the difference between the two assumptions. High-speed rail investment is, however, closer to a permanent injury as the rail tracks are intended to be long-lasting, and should thus be more reasonable to consider the impact permanent rather than treating it as a temporary injury.

Table 60 indicates each path's operation cost consumption in a 20-to-50 year time period. As shown, Path 5 requires the highest costs because its annual operation cost is the highest. Paths 2 and 4 are the least costly options shown. The difference between Path 2 (= Path 4) and Path 5 in terms of a 20-year timeframe is about $367.6 million and over a 50-year time span is about $919.1 million. This is because the total length between the two differs (15.7km = 249.3km – 233.6km). Figure 37 illustrates the result in a linear diagram format.

Table 60 Operation & Maintenance Costs in Different Operating Periods

Rank	Path	20 years	30 years	40 years	50 years
3	Path 1	$8,626,513,921	$12,939,770,882	$17,253,027,842	$21,566,284,803
1	Path 2	**$8,441,531,054**	**$12,662,296,581**	**$16,883,062,108**	**$21,103,827,635**
2	Path 3	$8,572,658,149	$12,858,987,225	$17,145,316,299	$21,431,645,374
1	Path 4	**$8,441,531,054**	**$12,662,296,581**	**$16,883,062,108**	**$21,103,827,635**
4	Path 5	**$8,809,155,233**	**$13,213,732,850**	**$17,618,310,466**	**$22,022,888,083**

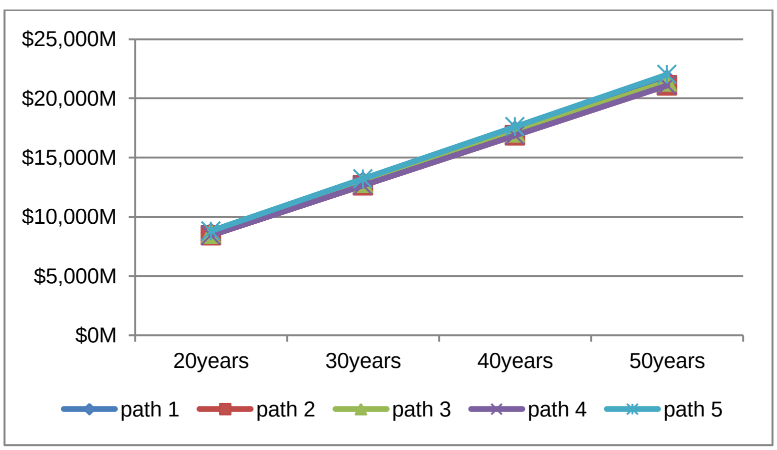


Figure 37 Operation Costs of Each Path for 20 to 50 Years Timeframe

Table 61 indicates each path's environmental costs within the same efficiency period. As shown, Path 5 consumes the least cost in environmental features, whereas Path 2 consumes the most environmental externalities. The difference between Path 5 and Path 1 in a 20-year time period is about $15.95 million, and in a 50-year timespan is about $39.87 million. Figure 38 illustrates the linear relationship. Unlike the operation costs shown in Figure 37, the difference between Paths 5 and 2 is distinctive, although the total values are much less.

Table 61 Environmental Costs in Different Operating Periods

Rank / Path		20years	30years	40years	50years
4	Path 1	$102,686,709	$154,030,063	$205,373,418	$256,716,772
5	Path 2	**$106,072,608**	**$159,108,911**	**$212,145,215**	**$265,181,519**
2	Path 3	$98,480,945	$147,721,418	$196,961,891	$246,202,364
3	Path 4	$100,723,106	$151,084,658	$201,446,211	$251,807,764
1	Path 5	**$90,125,483**	**$135,188,224**	**$180,250,966**	**$225,313,707**

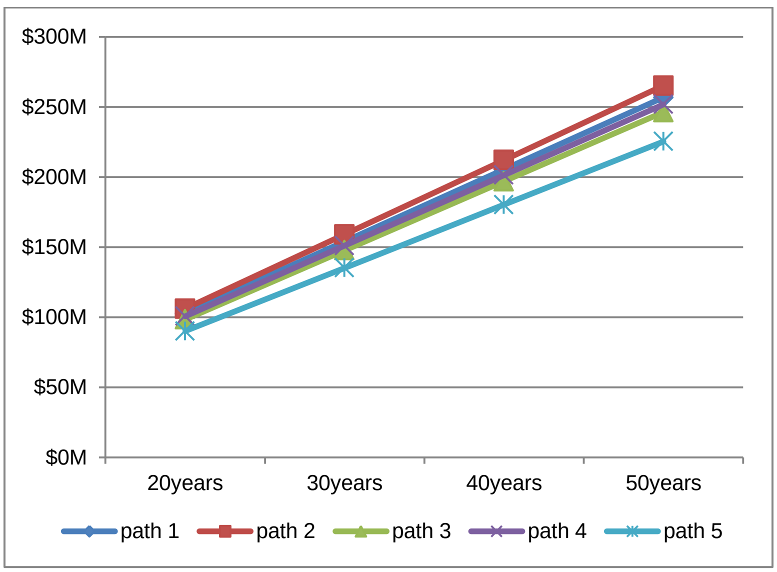


Figure 38 Environmental Costs of Each Path for 20 to 50 Years Timeframe

Table 62 and Figure 39 show the total recurring costs for each variable over the different time frames. They indicate that Path 5 consumes the highest recurring costs throughout the years, whereas Path 4 requires the least. As Paths 3, 4, and 5 are designed to avoid environmental variables and Paths 1 and 2 are intended to consider socio-economic and built environment variables, the annual environmental costs are the only difference in the recurring cost section. As identified in Table 61, Paths 1 and 2 consume higher environmental costs than the other options. The difference between Paths 4 and 5 in terms of the total recurring costs is approximately $357 million over 20 years and $892 million over 50 years, and this is due to the substantial difference in operation costs.

Table 62 Total Recurring Costs with Different Operating Periods

Rank / Path		20years	30years	40years	50years
4	Path 1	$8,729,200,630	$13,093,800,945	$17,458,401,260	$21,823,001,575
2	Path 2	$8,547,603,662	$12,821,405,492	$17,095,207,323	$21,369,009,154
3	Path 3	$8,671,139,095	$13,006,708,643	$17,342,278,190	$21,677,847,738
1	Path 4	**$8,542,254,160**	**$12,813,381,239**	**$17,084,508,319**	**$21,355,635,399**
5	Path 5	**$8,899,280,716**	**$13,348,921,074**	**$17,798,561,432**	**$22,248,201,770**

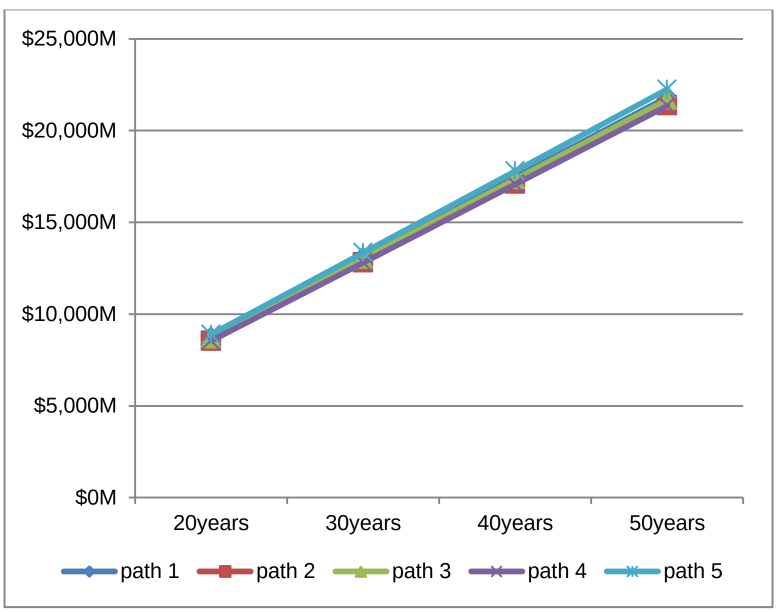


Figure 39 Total Recurring Costs of Each Path for 20 to 50 Years Timeframe

5.5.3 Total Cost Summary

The total cost analysis resulted in Path 5 being the most expensive route option and Path 4 the least costly alternative. There are differences in construction cost, however, and Table 63 summarizes the result.

Table 63 Summary of Total Cost for Each Path (in million $)

Cost Elements		Path1	Path2	Path3	Path4	Path5
Construction Cost		$6,475.57M	**$6,248.00M**	$6,352.53M	$6,251.53M	**$6,999.45M**
Operation Cost	Year1	$431.33M	**$422.08M**	$428.63M	**$422.08M**	**$440.46M**
	At Year20	$8,626.51M	$8,441.53M	$8,572.66M	$8,441.53M	$8,809.16M
	At Year30	$12,939.77M	$12,662.30M	$12,858.99M	$12,662.30M	$13,213.73M
	At Year40	$17,253.03M	$16,883.06M	$17,145.32M	$16,883.06M	$17,618.31M
	At Year50	$21,566.28M	$21,103.83M	$21,431.65M	$21,103.83M	$22,022.89M
Environ. Cost (Median)	Year1	$5.13M	**$5.30M**	$4.92M	$5.04M	**$4.51M**
	At Year20	$102.69M	$106.07M	$98.48M	$100.72M	$90.13M
	At Year30	$154.03M	$159.11M	$147.72M	$151.08M	$135.19M
	At Year40	$205.37M	$212.15M	$196.96M	$201.45M	$180.25M
	At Year50	$256.72M	$265.18M	$246.20M	$251.81M	$225.31M
Total	In 20 years	$15,204.77M	$14,795.60M	$15,023.67M	**$14,793.78M**	**$15,898.73M**
	In 50 years	$28,298.57M	$27,617.01M	$28,030.38M	**$27,607.16M**	**$29,247.66M**

Implementing Path 4 will require $6.3 billion for construction in addition to the annual costs of $422.08 million for operation and $5.04 million for environmental externalities. On the other hand, Path 5 would require $7 billion for its construction as well as the annual costs of $440.46 million for operation and $$4.51 million for environmental features.

Although the environmental cost of Path 5 indicates the least expensive option, it still is the most costly HSR route considering all three cost attributes. The main reason can be traced to its substantial difference in construction cost. As the construction cost element consists of to 43% for the 20 years of the total cost, while the environmental costs only makes up about 1%, a 20-year timeframe cannot compensate for the loss in construction costs. The difference between Paths 2 and 5 in terms of construction cost is about $751.5 million. And the difference between the two in terms of environmental costs even for a 50-year timespan only accounts for about $40 million. Therefore, it would take about 940 years to fully compensate for the costs accrued during the initial construction with the environmental externalities.

However, there are some interesting results that could arguable be said to partially support the main hypotheses and they will be elaborated in the result section.

6. RESULT

As described in Section 3.2, the main hypothesis of this dissertation is to test the difference in total cost between routes designed with environmental variables in mind at the beginning of the planning stage, and those focused more on built environment variables such as population density, job density, and land use. Using the raster-based GIS modeling process, a total of five different route options were extracted. Of those alternatives, two (Paths 1 & 2) are geared toward socio-economic and built environment variables, and three (Paths 3, 4, & 5) are based on natural resource variables. Below are the two main hypotheses.

- **Hypothesis#1-1:** *The routes optimized with environmental variables such as water or ground resource variables, consume less total cost than the route options optimized with socio-economic or built-environment variables.*

- **Hypothesis#1-2:** *The more inclusive economic values of environmental services offer a lower total cost due to the economic benefits from the preserved ecosystem features.*

In order to support the above two hypotheses, all of Paths 3, 4, and 5 should cost less in terms of their total cost compared to Paths 1 and 2. As can be seen in Table 63, however, the total cost of Path 4 came out as the most efficient and Path 5 as the priciest option for an HSR route linking Austin and Houston. In other words, the main hypotheses are not fully supported because of the significant construction and operation costs in Path 5, which is designed with the environmental features such as farmland, vegetation, and slope variables in mind. In order for the above hypotheses to be valid, either Path 1 or 2 should have been the most costly alternative when all three cost elements were considered over the same project evaluation period.

As briefly mentioned, the main reason for this can be traced to the significant difference in construction and operation costs. In Table 41 and 43, the difference between Paths 4 and 5 in terms of construction cost is about $748 million and about $17 million per year in terms of operation cost. On the other hand, the difference in the environmental cost, the only category where Path 5 is less costly than Path 4, Path 5 is about $0.53 million per year less costly than Path 4. Therefore, Path 5 cannot overcome the economic burden in construction cost even when the environmental cost is summed over a 50-year timeframe ($0.53 million x 50 years = $26.5 million). It only compensates for about 4% of the loss in construction costs ($26.5 million / $748 million = 0.036). In order for the preserved environmental benefits of Path 5 to fully pay back the difference in construction costs of Path 4, $748 million, it would take about 1,400 years. In this sense, it would be plausible to say that the difference in construction costs is the biggest element driving the total cost of each route alternative.

However, it is not possible to absolutely reject the main hypotheses as the total costs of Paths 3 and 4 show less costly alternatives than Paths 1 and 2. As seen in Tables 59 and 62, the total costs of building Path 3 is much less than the total cost to build Path 1. The difference between the two alternatives is about $126 million. Specifically, Path 1 requires $123 million more in construction cost and $2.7 million more in annual operation costs. Path 3 is designed to preserve ground resources such as geology, aquifers, and precipitation. Using such variables made Path 3 avoids soft grounds and shifts toward more preferred soils than Path 1 (See Table 41). Doing so also created a shorter route in terms of total length (241.5 km vs. 239.2 km). Consequently, thorough consideration on ground resources positively influenced construction and operation costs (See Tables 59 and 63).

In addition, as Path 3 is geared more toward preservation of environmental variables, environmental costs differ as well. The difference between Paths 1 and 3 in terms of environmental externalities is about $0.2 million per year. Except Urban Open Space and Pasture, all the other categories in environmental costs for Path 3 are less costly than Path 1 (See Table 52). If implemented within the evaluation period, the difference ranges from \$4.2 million in 20 years to \$10.5 million in 50 years (Path 1 is greater than Path 3). As explained earlier, environmental costs are calculated as permanent injuries because a railroad is built to last longer than other infrastructure investments.

Another noteworthy result can be found in the comparison between Paths 2 and 4. As mentioned in Table 43, these two routes' lengths are the same (233.6 km). In other words, their costs based on total length will be identical. As can be seen in Table 46, total operation costs for Paths 2 and 4 are indistinguishable. This is because the calculation of operation costs are largely based on the route's total length, and the same rule applies to the value of time. Therefore, the only possible differences between the two options are a few categories in construction costs as some of them are also based on geologic and hydrologic units, and in environmental costs.

As can be seen in Table 41, Path 4 requires about \$3.53 million more than Path 2 for its construction. Path 4 costs about \$3 million more in land compensation as it passes higher value housing units than does Path 2 (See Table 40). Although the effected number of housing units for Path 4 is less than Path 2, the total housing value estimate is greater. In addition, Path 4 requires about \$17.6 million more than Path 2 in overpass bridge construction. Path 2 is designed to avoid the built environment variables, such as roads and land use, and the road network is the main reason for building overpass bridges. As mentioned earlier when describing each variable, the more the HSR route passes major highways, the pricier the construction becomes.

On the other hand, Path 4 requires about \$14.5 million less in normal bridge construction. This is an expected result as Path 4 is designed to minimize the impact on water resource variables, such as hydrologic units, floodplain, and wetlands. Therefore, the possibility of constructing a normal bridge should be less than any other route alternatives (See

Table 41). Also, there is about $2.6 million difference in civil work as well. In all, Path 4 requires $3.53 million more in construction cost than Path 2.

When environmental costs are considered, however, Path 4 destructs less environmental systems than does Path 2. Using the median values, Path 4 consumes about $0.27 million less than Path 2 ($5.3 million vs. $5.04 million annually). In other words, constructing Path 4 requires $3.53 million more at the beginning of construction. But in the 14th year of operation, the induced loss in construction costs will be fully compensated for by the preserved benefits in environmental features ($0.27 million x 14 years = $3.74 million, greater than $3.53 million). This is an interesting result because it partially supports the first main hypothesis.

Table 64 Summary of Environmental Cost Difference between Path 2 & 4

(Annual measure: $/year)	**Path 2**	**Path 4**	**Difference (Path 2 – Path 4)**
Open Water	$60,442	$35,680	$24,762
Urban Open Space	$546,640	$1,144,875	-$598,235
Forest	$379,590	$265,817	$113,773
Shrub	$11,159	$10,354	$805
Herb	$7,320	$6,968	$352
Pasture	$3,601,693	$3,385,418	$216,275
Crop	$7,193	$6,879	$314
Wet	$678,871	$175,875	$502,996
River	$10,723	$4,289	$6,434
Total	**$5,303,630**	**$5,036,155**	**$267,475**

Figure 40 illustrates this relationship. In the 14th year of operation, the total costs of Path 2 surpass the total costs of Path 4. As can be seen in Table 64, except for Urban Open Spaces, all the other environmental categories in Path 4 cost significantly less than the same categories in Path 2. For Urban Open Space, Path 4 is about $0.6 million per year more expensive than Path 2. However, this loss is easily made up by the gains in the other features, such as Wetland services as Path 4 costs $0.5 million less than Path 2 for the wetland service category.

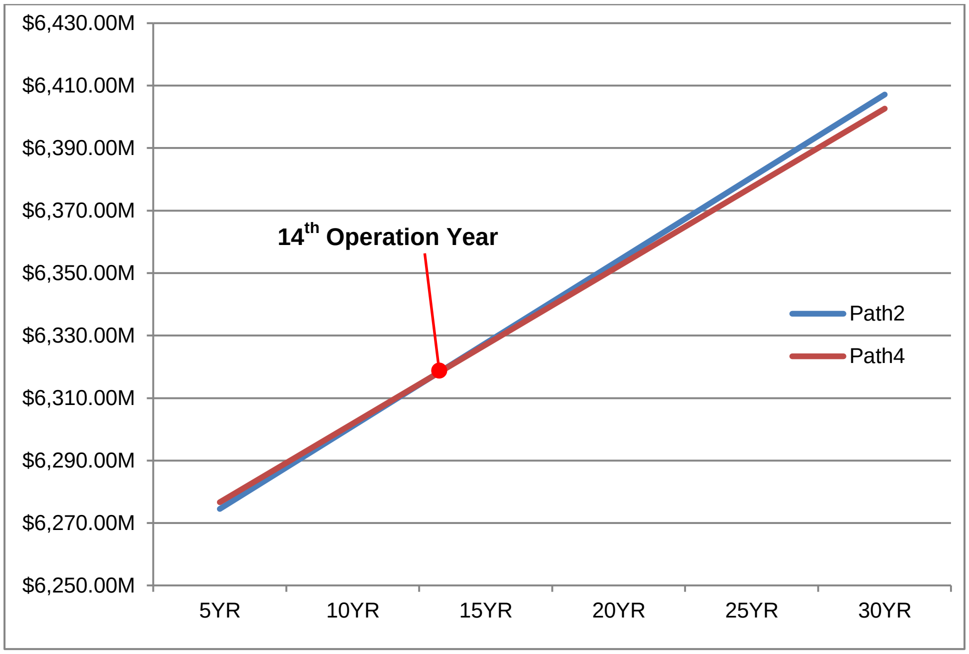


Figure 40 Cost Shift in a 30-Year Timeframe

In sum, constructing Path 4 for the Austin-to-Houston segment would be the most sustainable HSR route with the given criteria. Compared to Path 1, it will save about $224 million in construction, about $9.3 million in annual operation expenses, and about $0.1 million in annual environmental resource consumption. Furthermore, compared to Path 5, Path 4 will save about $747.9 million in construction, and about $18.4 million in its annual operation costs. However, it would cost about $0.53 million more in annual environmental externalities. Finally, compared to Path 2, the most similar option in terms of total cost, Path 4 will require about $3.53 million more in its construction. Nonetheless, in the 14^{th} operation year, this loss will be compensated for by the economic values of preserved environmental resources such as wetlands, pasture, and forest.

Based on the comparison between Paths 2 and 4, even though the main hypotheses are not fully supported, it could be argued that the costs saved in environmental externalities can compensate for the expenditures in fixed, internal costs. If the length-based costs are similar and the difference in initial investment between the routes is not significant, the economic benefits of the preserved ecosystem features can pay back the initial induced losses, such as construction cost, over a longer time period. Figure 41 illustrates Paths 2 and 4 within the study site.

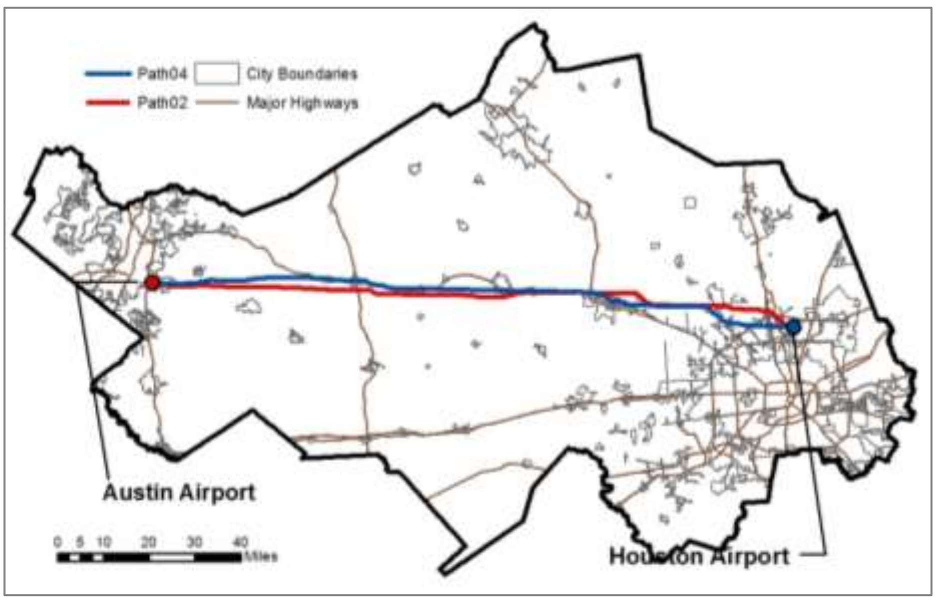


Figure 41 Path 2 & 4 in the Study Area

7. CONCLUSION & LIMITATIONS

The research model in this dissertation is designed to resolve the two big issues in an investment decision-making by merging a decision-support system and a transportation project evaluation. As discovered earlier, the first problem is in decision system science, especially GIS-based decision support systems. Lack of objective and scientific method to apply weights to input variables and the limited capability to involve public opinion are identified as the two largest shortcomings in current spatial decision support system (SDSS) practice. Existing literature suggests possible solutions as scenario planning and variable grouping.

An analytic method has been added to the existing SDSS developed by previous research works (Kim, Wunneburger et al. 2011) to correspond to the solutions identified above. Confirmatory factor analysis (CFA) allowed alternative HSR routes to be drawn. Section 4.1.4 is specifically dedicated to the use of CFA in this dissertation. CFA provided a number of groups of variables with each variable's statistical significance. By doing so, the model avoids allocating indistinctive weights to a large pool of variables. Variables are categorized by their underlying similarities and thus, each group possesses its unique proposition and provides different types of benefits and costs. As summarized in Table 26, five different possibilities in route optimization are suggested. Accordingly, five different HSR route options are extracted using the cost surface and the shortest path analysis in GIS. Merging CFA to the existing SDSS opened a margin to incorporate scenario planning and variable grouping process in a more systematic manner.

Furthermore, three possible points were identified at which the SDSS can develop a more participatory decision-making environment. Although the limitations in the weighting process have been relieved through the implementation of CFA, the current SDSS still lacks diversity of merging public opinions. First, users can design and tailor their input variables based on their own interest. This is possible at the first stage of the modeling process. As identified in Figure 11 and Table 5, the current practice relies solely on experts' opinion. If the related stakeholders can set the input variables of their interest, the entire modeling process will become a more user-oriented environment. The second possibility is in the variable classification process. As seen in Section 4.1.3, each variable needs to be reclassified to fit into a unified scale. At this point, both experts and users can collaborate to set the reclassification system and the overall meaning of variables to the final objective. Finally, stakeholders can actively express their inputs on the external weighting process. Based on the grouping process, users can insert their opinions to the suggested development scenarios and the anticipated route outcomes. The Analytic Hierarchy Process (AHP) articulated in Section 4.1.6 is a good way to handle inputs from the users and calculate the weights in a numeric format.

By incorporating CFA and identifying three points of participation, the first limitation in the current investment decision process significantly improves. Merging CFA and public involvement will create a more user-friendly modeling environment, and greatly advances the utilization of SDSS in various disciplines.

The second issue elaborated in the literature review section concerns alternative interpretations with environmental externalities. Previous practices of decision support systems provide a range of alternatives, but their precise meaning is not definite. To minimize such vagueness, the idea of transportation project evaluation has been implemented throughout the overall modeling process. Specifically, the suitability score matrix and total cost analysis have been adapted to the route interpretation process. The suitability matrix shows the validity of each path's intended purpose. For example, a path designed with water resource variables should show higher suitability scores on hydrologic units and wetland variables than the other path options. Furthermore, the suitability matrix enables the acquisition of pixel values, and pixel values can easily transform to area information by simply multiplying the number of pixels in each route. By doing so, expected resource consumptions such as the areas of forest intersected by a route are precisely quantified.

Total cost analysis is intended to incorporate environmental externalities in the project evaluation process. As discussed previously, project evaluation in the U.S. often leaves out environmental costs from consideration, while hinging on construction and operation costs when selecting transportation projects. In addition, the traditional environmental impact analysis, which is a frequently-used substitute to measure the impact of a project on environmental features, is conducted with a scoring system. In this sense, the degree of impact on the natural asset is hard to pinpoint in terms of cost. To confront such issues, environmental features are calculated here as an opportunity cost.

As mentioned earlier, each route's consumption of each variable is accessible through the suitability score matrix, which can easily be converted into area information because the number of cells and their values are readable in the matrix. Using this information, the areas of natural assets impinged upon by a train route are estimated. After that, using previous study results, the unit environmental costs ($/acre/year) are estimated. Finally, the environmental area information is multiplied by the unit costs of each land cover type. This entire approach is known as value transfer. The output costs are a good proxy measure of environmental externalities associated with each path and development scenario at large.

Examining the suitability matrix gives information about the scale of resource consumption by each route. Such information is easily accessible because the modeling process is based on raster datasets. Not only are the construction and operation costs estimable using the route length and ridership information, environmental externalities are calculable using the value transfer approach. Combining the two, the major shortcoming, lack of precise measurement on the final alternatives of SDSS, can be significantly relieved because the outcome options are now precisely comparable in terms of anticipated total costs.

Although the main hypotheses are not fully supported, the framework for infrastructure investment decision-making suggested in this dissertation is meaningful. By using CFA, variable grouping and scenario building are enabled in a quantitative manner. CFA also relieved the lack of objectivity in the weighting process. Three possible participation points are also suggested to ameliorate the other limitation known to current SDSS practice. In addition, the suitability matrix and total cost analysis eased the second limitation. Incorporating value transfer allowed estimation of environmental externalities as an opportunity cost and enabled route interpretation and comparison in a more systematic manner. According to the analysis result, if the differences in fixed costs are not too significant, economic benefits of the preserved environmental services outweigh the larger construction and operation costs over a longer time period.

Nonetheless, there are limitations in this modeling process, and they can be summarized in three folds. First, the proposed and tested SDSS may have problems in data acquisition and validity. Although spatial datasets are widely adopted data types in recent urban planning discipline, many datasets are still hard to access. For example, population density was calculated using the decennial census provided by the U.S. Census Bureau. The decennial census can be acknowledged as the most precise population information, and thus utilized to estimate the possible allocation of people and goods. The problem is that the dataset does not precisely represent the latest population trends. In other words, population density may contain dated information, and thus may provide false implications for the socio-economic variables. In addition, some datasets, such as parcel values, are not completely open to the public or accessible without costs. Therefore, a proxy measure, in this case median housing values inside a census tract is implemented to estimate the anticipated land acquisition fees. This is a plausible approach but does not qualify for an absolute substitute.

The second limitation is in calculating environmental externalities. The value transfer method is handy for estimating expected environmental losses in terms of economic values. However, as the approach relies on existing studies, values may possess validity issues. Although the Consumer Price Index (CPI) was implemented to convert the dollar values to the present, it still lacks the complete representation of the current year. Furthermore, spatial heterogeneity may cause some issues in value transfer. Some places' environmental costs may differ from those in other places as their spatial circumstances may vary. Therefore, caution is warranted when collecting study results for use as reference for value transfer.

A final possible criticism of this study would be the use of Korean HSR specifications in construction and operation costs. This dissertation implemented the Korean HSR specifications because the Texas Urban Triangle research was partially funded by a Korean engineering firm. The sponsor not only provided a research grant, but also made specific information about the Korean HSR available for this analysis. Using this information, two fixed cost elements were estimated, but we cannot be sure whether the TUT would implement HSR similar to that of Korean or lean toward a European model. Therefore, using specific HSR cost information does not fully represent the possible internal costs for the TUT area.

As this study is closer to developing a systematic decision framework, however, a few different remedies can be suggested to relieve the abovementioned shortcomings. First, the cost issue of data acquisition can be eased if this framework is to be used for precise design of the route in the TUT area. If an HSR is to be implemented, detailed measurements are crucial parts of investigation, and paying the corresponding costs would be reasonable for obtaining the necessary datasets.

Lack of validity in value transfer can be solved with other strategic tactics. In the ecological economics discipline, there are different types of environmental cost modeling such as contingent valuation, hedonic pricing, or replacement cost (Costanza 2000; Wilson, Troy et al. 2004). Some are based on more sophisticated statistical models, while others rely on stated preference surveys. If time and cost permit, a separate and independent model can be designed to measure the environmental cost specifically for the study area. Issues in the Korean HSR unit cost can also be ameliorated by replacing its specifications with a different HSR's. This dissertation is closer to providing a decision framework and thus, once the rail and vehicle types are decided, specific cost information on construction and operation of the selected HSR could be input into the fixed cost sections.

This dissertation provided initial solutions and options that could be utilized in future projects. One of the greatest advantages in using the proposed SDSS is that whichever specifications, input variables, or modeling methods are used, the decision framework remains the same. The decision framework can work with and adapt to various types of variables and cost information, and generate corresponding outcome values with unified interpretation and comparison parameters. If necessary data are acquired, all the outcome alternatives will have the same criteria for their evaluation.

Decision makers can modify the SDSS contingent upon appropriate circumstances, and can interpret the results according to prevailing decision criteria such as politics and economics with the data used in this dissertation as an example. If we are concerned more with conflicts resulting from the relocation of people and property, we may choose Path 1 or Path 2. In addition, if we care less about environmental externalities, Path 2 would have been the most suitable option for an HSR for the Austin-to-Houston segment. However, considering the environmental impact as an opportunity cost enabled a more accurate total cost comparison, and exposed some precise advantages for choosing Path 4 instead of Path 2. Being able to calculate environmental externalities in terms of a cost element gives a different insight on a transportation project and should not be ignored in other types of decision-making as well.

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APPENDIX A

```
                    DATE: 12/27/2012
                      TIME: 21:23

           LISREL 8.80 (STUDENT EDITION)
                          BY
           Karl G. Jöreskog & Dag Sörbom

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C:\Users\Hwan\Desktop\Dissertation\05_CFA\8000CFA_Sample01_10292012.LS8:

 8000Meeting01 CFA Hwanyong Kim

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 occ est pop Noise lu Road Aquif Geo Precip Hydro Wet Flood Slope30 Farm Vege

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 mo ny=15 ne=5 ly=fu,fr ps=sy,fr te=sy,fr

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 LatentA LatentB LatentC LatentD LatentE

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PATH DIAGRAM

ou nd=3  mi sc

8000Meeting01 CFA Hwanyong Kim

                         Number of Input Variables 15
                         Number of Y - Variables   15
                         Number of X - Variables    0
                         Number of ETA - Variables  5
                         Number of KSI - Variables  0
                         Number of Observations  7990

8000Meeting01 CFA Hwanyong Kim

        Covariance Matrix

                 occ         est         pop       Noise          lu        Road
            --------    --------    --------    --------    --------    --------
      occ      2.021
      est      0.320       0.455
      pop      0.521       0.437       0.708
    Noise      0.646       0.592       0.725       2.124
       lu      0.299       0.343       0.457       0.667       0.711
     Road      0.103       0.105       0.149       0.215       0.223       0.408
    Aquif      0.147       0.087       0.140       0.150       0.104       0.032
      Geo      0.264       0.014       0.080       0.015       0.058       0.013
   Precip      0.463       0.196       0.350       0.395       0.311       0.078
    Hydro      0.005       0.012       0.008       0.058      -0.018      -0.017
      Wet      0.039      -0.026      -0.037      -0.037      -0.077      -0.043
    Flood      0.069      -0.020      -0.029       0.004      -0.076      -0.048
  Slope30     -0.551      -0.212      -0.311      -0.394      -0.241      -0.076
     Farm     -0.581      -0.397      -0.585      -0.767      -0.433      -0.138
     Vege     -0.383      -0.358      -0.487      -0.770      -0.667      -0.269

        Covariance Matrix
               Aquif         Geo      Precip       Hydro         Wet       Flood
```

Aquif	0.840					
Geo	0.085	1.531				
Precip	0.424	0.571	1.353			
Hydro	-0.001	0.037	0.028	0.338		
Wet	0.013	0.079	0.084	0.055	0.702	
Flood	-0.006	0.317	0.127	0.217	0.293	1.408
Slope30	-0.212	-0.534	-0.550	-0.042	-0.016	-0.278
Farm	-0.217	-0.171	-0.522	-0.053	-0.002	-0.083
Vege	-0.194	-0.267	-0.545	-0.171	-0.528	-0.320

Covariance Matrix

	Slope30	Farm	Vege
Slope30	2.320		
Farm	0.575	2.057	
Vege	0.476	0.430	2.343

Parameter Specifications

LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	1	0	0	0	0
est	2	0	0	0	0
pop	3	0	0	0	0
Noise	0	4	0	0	0
lu	0	5	0	0	0
Road	0	6	0	0	0
Aquif	0	0	7	0	0
Geo	0	0	8	0	0
Precip	0	0	9	0	0
Hydro	0	0	0	10	0
Wet	0	0	0	11	0
Flood	0	0	0	12	0
Slope30	0	0	0	0	13
Farm	0	0	0	0	14
Vege	0	0	0	0	15

PSI

	LatentA	LatentB	LatentC	LatentD	LatentE
LatentA	0				
LatentB	16	0			
LatentC	17	18	0		
LatentD	19	20	21	0	
LatentE	22	23	24	25	0

THETA-EPS

occ	est	pop	Noise	lu	Road
26	27	28	29	30	31

THETA-EPS

Aquif	Geo	Precip	Hydro	Wet	Flood
32	33	34	35	36	37

THETA-EPS

Slope30	Farm	Vege
38	39	40

Number of Iterations = 27

LISREL Estimates (Maximum Likelihood)

LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	0.636 (0.016) 40.302	- -	- -	- -	- -
est	0.562 (0.006) 87.588	- -	- -	- -	- -
pop	0.778 (0.008) 101.974	- -	- -	- -	- -
Noise	- -	0.981 (0.015) 64.501	- -	- -	- -
lu	- -	0.702 (0.008) 84.019	- -	- -	- -
Road	- -	0.267 (0.007) 36.851	- -	- -	- -
Aquif	- -	- -	0.351 (0.011) 30.795	- -	- -
Geo	- -	- -	0.475 (0.015) 30.843	- -	- -
Precip	- -	- -	1.209 (0.022) 54.507	- -	- -
Hydro	- -	- -	- -	0.182 (0.008) 23.669	- -
Wet	- -	- -	- -	0.547 (0.012) 46.591	- -
Flood	- -	- -	- -	0.529 (0.015) 34.198	- -
Slope30	- -	- -	- -	- -	0.374 (0.016) 22.735
Farm	- -	- -	- -	- -	0.581 (0.017) 35.054
Vege	- -	- -	- -	- -	0.983 (0.019) 51.637

Covariance Matrix of ETA

LatentA	LatentB	LatentC	LatentD	LatentE

LatentA	1.000				
LatentB	0.869	1.000			
LatentC	0.356	0.352	1.000		
LatentD	-0.061	-0.157	0.139	1.000	
LatentE	-0.800	-0.969	-0.562	-0.706	1.000

PSI

	LatentA	LatentB	LatentC	LatentD	LatentE
LatentA	1.000				
LatentB	0.869	1.000			
	(0.006)				
	139.629				
LatentC	0.356	0.352	1.000		
	(0.012)	(0.013)			
	30.199	27.922			
LatentD	-0.061	-0.157	0.139	1.000	
	(0.016)	(0.017)	(0.015)		
	-3.738	-8.984	9.346		
LatentE	-0.800	-0.969	-0.562	-0.706	1.000
	(0.014)	(0.014)	(0.017)	(0.020)	
	-58.855	-67.185	-33.660	-34.775	

THETA-EPS

occ	est	pop	Noise	lu	Road
1.616	0.139	0.103	1.161	0.219	0.337
(0.026)	(0.003)	(0.005)	(0.021)	(0.006)	(0.005)
61.571	44.012	22.479	55.514	37.070	61.390

THETA-EPS

Aquif	Geo	Precip	Hydro	Wet	Flood
0.717	1.306	-0.110	0.305	0.403	1.128
(0.012)	(0.022)	(0.049)	(0.005)	(0.011)	(0.020)
59.610	59.577	-2.223	60.091	36.305	55.789

THETA-EPS

Slope30	Farm	Vege
2.180	1.720	1.377
(0.034)	(0.028)	(0.031)
63.363	61.113	44.076

Squared Multiple Correlations for Y - Variables

occ	est	pop	Noise	lu	Road
0.200	0.695	0.855	0.453	0.693	0.175

Squared Multiple Correlations for Y - Variables

Aquif	Geo	Precip	Hydro	Wet	Flood
0.147	0.147	1.081	0.098	0.427	0.199

Squared Multiple Correlations for Y - Variables

Slope30	Farm	Vege

```
               0.060      0.164      0.412

                          Goodness of Fit Statistics

                            Degrees of Freedom = 80
               Minimum Fit Function Chi-Square = 5389.809 (P = 0.0)
       Normal Theory Weighted Least Squares Chi-Square = 5567.462 (P = 0.0)
               Estimated Non-centrality Parameter (NCP) = 5487.462
          90 Percent Confidence Interval for NCP = (5246.378 ; 5735.749)

                       Minimum Fit Function Value = 0.675
                Population Discrepancy Function Value (F0) = 0.687
             90 Percent Confidence Interval for F0 = (0.657 ; 0.718)
             Root Mean Square Error of Approximation (RMSEA) = 0.0927
           90 Percent Confidence Interval for RMSEA = (0.0906 ; 0.0947)
               P-Value for Test of Close Fit (RMSEA < 0.05) = 0.000

                  Expected Cross-Validation Index (ECVI) = 0.707
            90 Percent Confidence Interval for ECVI = (0.677 ; 0.738)
                        ECVI for Saturated Model = 0.0300
                       ECVI for Independence Model = 7.074

    Chi-Square for Independence Model with 105 Degrees of Freedom = 56482.018
                           Independence AIC = 56512.018
                               Model AIC = 5647.462
                             Saturated AIC = 240.000
                          Independence CAIC = 56631.807
                              Model CAIC = 5966.900
                            Saturated CAIC = 1198.314

                          Normed Fit Index (NFI) = 0.905
                       Non-Normed Fit Index (NNFI) = 0.876
                    Parsimony Normed Fit Index (PNFI) = 0.689
                       Comparative Fit Index (CFI) = 0.906
                       Incremental Fit Index (IFI) = 0.906
                         Relative Fit Index (RFI) = 0.875

                            Critical N (CN) = 167.504

                      Root Mean Square Residual (RMR) = 0.105
                            Standardized RMR = 0.0691
                       Goodness of Fit Index (GFI) = 0.915
                  Adjusted Goodness of Fit Index (AGFI) = 0.872
                  Parsimony Goodness of Fit Index (PGFI) = 0.610

Modification Indices and Expected Change

         Modification Indices for LAMBDA-Y

             LatentA    LatentB    LatentC    LatentD    LatentE
            --------   --------   --------   --------   --------
      occ       - -      22.577    151.735     70.052     14.767
      est       - -      80.653    153.534     13.467      6.797
      pop       - -      38.124     53.520      0.206     17.147
    Noise    563.849       - -       3.524     16.809    105.414
       lu    214.258       - -      20.374      3.964     47.603
     Road    187.806       - -      27.097     11.661     24.963
    Aquif     33.948     34.622       - -       0.046      0.009
      Geo     52.889     51.702       - -     185.694      2.358
   Precip      1.515      1.353       - -      99.655      1.302
    Hydro     15.571     15.607      0.393       - -       5.639
      Wet      5.518      0.418      4.160       - -      37.518
    Flood      0.033      4.419      7.452       - -      24.378
```

Slope30	87.386	78.934	311.706	15.827	- -
Farm	790.685	434.451	89.309	403.371	- -
Vege	956.549	613.862	342.516	266.245	- -

Expected Change for LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	- -	-0.197	0.183	0.145	-0.076
est	- -	0.214	-0.064	-0.022	-0.019
pop	- -	-0.213	0.051	0.004	0.042
Noise	1.012	- -	-0.027	0.071	-0.206
lu	-0.424	- -	0.043	-0.023	0.093
Road	-0.261	- -	-0.036	-0.028	0.046
Aquif	0.071	0.074	- -	0.003	-0.001
Geo	-0.119	-0.122	- -	0.216	0.023
Precip	0.043	0.045	- -	-0.290	-0.034
Hydro	0.027	0.027	-0.004	- -	-0.015
Wet	-0.031	-0.009	-0.025	- -	0.080
Flood	-0.003	-0.030	0.036	- -	-0.069
Slope30	-0.252	-0.249	-0.338	-0.090	- -
Farm	-0.738	-0.596	-0.174	0.475	- -
Vege	1.251	1.113	0.524	-0.613	- -

Standardized Expected Change for LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	- -	-0.197	0.183	0.145	-0.076
est	- -	0.214	-0.064	-0.022	-0.019
pop	- -	-0.213	0.051	0.004	0.042
Noise	1.012	- -	-0.027	0.071	-0.206
lu	-0.424	- -	0.043	-0.023	0.093
Road	-0.261	- -	-0.036	-0.028	0.046
Aquif	0.071	0.074	- -	0.003	-0.001
Geo	-0.119	-0.122	- -	0.216	0.023
Precip	0.043	0.045	- -	-0.290	-0.034
Hydro	0.027	0.027	-0.004	- -	-0.015
Wet	-0.031	-0.009	-0.025	- -	0.080
Flood	-0.003	-0.030	0.036	- -	-0.069
Slope30	-0.252	-0.249	-0.338	-0.090	- -
Farm	-0.738	-0.596	-0.174	0.475	- -
Vege	1.251	1.113	0.524	-0.613	- -

Completely Standardized Expected Change for LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	- -	-0.139	0.129	0.102	-0.054
est	- -	0.317	-0.095	-0.032	-0.029
pop	- -	-0.253	0.061	0.004	0.050
Noise	0.694	- -	-0.019	0.049	-0.141
lu	-0.502	- -	0.052	-0.027	0.110
Road	-0.409	- -	-0.056	-0.044	0.072
Aquif	0.077	0.081	- -	0.003	-0.001
Geo	-0.096	-0.099	- -	0.174	0.019
Precip	0.037	0.038	- -	-0.250	-0.030
Hydro	0.046	0.047	-0.007	- -	-0.026
Wet	-0.037	-0.010	-0.030	- -	0.096
Flood	-0.002	-0.026	0.030	- -	-0.058
Slope30	-0.166	-0.163	-0.222	-0.059	- -
Farm	-0.515	-0.416	-0.122	0.331	- -
Vege	0.817	0.727	0.343	-0.400	- -

No Non-Zero Modification Indices for PSI

Modification Indices for THETA-EPS

	occ	est	pop	Noise	lu	Road
occ	- -					
est	74.541	- -				
pop	97.684	7.479	- -			
Noise	27.190	284.242	0.179	- -		
lu	130.714	7.355	43.866	91.806	- -	
Road	5.697	23.731	30.149	54.100	238.814	- -
Aquif	2.437	4.908	4.632	0.341	18.745	0.038
Geo	57.793	23.596	0.358	29.931	10.584	0.066
Precip	62.810	87.883	29.658	0.260	50.756	13.527
Hydro	6.637	15.176	0.240	92.331	29.338	11.947
Wet	2.628	3.527	13.273	28.559	44.369	7.847
Flood	7.449	1.709	1.406	60.848	0.046	2.882
Slope30	187.457	4.555	3.414	20.732	131.299	14.161
Farm	38.218	0.273	232.100	1.488	162.135	23.930
Vege	16.905	13.050	44.544	147.279	466.877	67.535

Modification Indices for THETA-EPS

	Aquif	Geo	Precip	Hydro	Wet	Flood
Aquif	- -					
Geo	78.453	- -				
Precip	1.447	50.723	- -			
Hydro	2.926	0.030	2.320	- -		
Wet	4.838	17.634	1.110	267.127	- -	
Flood	19.506	217.145	0.002	415.788	0.976	- -
Slope30	12.375	283.915	19.211	5.211	329.590	34.339
Farm	25.214	2.463	14.956	0.209	283.184	24.331
Vege	11.422	23.161	172.795	8.037	1171.616	211.060

Modification Indices for THETA-EPS

	Slope30	Farm	Vege
Slope30	- -		
Farm	286.170	- -	
Vege	36.924	203.263	- -

Expected Change for THETA-EPS

	occ	est	pop	Noise	lu	Road
occ	- -					
est	-0.055	- -				
pop	0.078	-0.024	- -			
Noise	0.085	0.094	0.003	- -		
lu	-0.091	0.008	-0.025	-0.134	- -	
Road	-0.020	-0.014	-0.018	-0.056	0.062	- -
Aquif	-0.019	0.009	0.010	-0.006	-0.022	-0.001
Geo	0.124	-0.026	-0.004	-0.079	-0.022	0.002
Precip	0.104	-0.042	0.031	-0.006	0.054	-0.022
Hydro	-0.021	0.010	-0.001	0.070	-0.020	-0.013
Wet	0.017	0.007	-0.016	0.054	-0.039	-0.014
Flood	0.043	0.007	-0.007	0.114	-0.002	-0.012
Slope30	-0.289	0.015	-0.015	0.088	0.113	0.037
Farm	-0.115	-0.003	-0.109	-0.021	0.119	0.042
Vege	0.065	0.019	0.046	0.203	-0.223	-0.063

Expected Change for THETA-EPS

	Aquif	Geo	Precip	Hydro	Wet	Flood
Aquif	- -					
Geo	-0.113	- -				
Precip	0.037	0.293	- -			
Hydro	-0.009	0.001	-0.009	- -		
Wet	-0.015	-0.039	0.011	-0.092	- -	
Flood	-0.046	0.207	0.001	0.148	0.016	- -
Slope30	-0.049	-0.315	-0.069	0.022	0.248	-0.112
Farm	-0.062	0.026	-0.058	-0.004	0.226	0.089
Vege	-0.036	-0.070	0.251	-0.024	-0.623	0.301

Expected Change for THETA-EPS

	Slope30	Farm	Vege
Slope30	- -		
Farm	0.375	- -	
Vege	0.128	-0.427	- -

Completely Standardized Expected Change for THETA-EPS

	occ	est	pop	Noise	lu	Road
occ	- -					
est	-0.058	- -				
pop	0.066	-0.043	- -			
Noise	0.041	0.096	0.002	- -		
lu	-0.076	0.014	-0.035	-0.109	- -	
Road	-0.022	-0.032	-0.033	-0.060	0.115	- -
Aquif	-0.014	0.014	0.012	-0.005	-0.029	-0.002
Geo	0.071	-0.031	-0.003	-0.044	-0.022	0.002
Precip	0.063	-0.053	0.032	-0.004	0.055	-0.030
Hydro	-0.025	0.026	-0.003	0.083	-0.040	-0.035
Wet	0.014	0.012	-0.022	0.044	-0.055	-0.026
Flood	0.026	0.009	-0.007	0.066	-0.002	-0.016
Slope30	-0.134	0.014	-0.011	0.040	0.088	0.038
Farm	-0.056	-0.003	-0.090	-0.010	0.099	0.046
Vege	0.030	0.019	0.036	0.091	-0.172	-0.064

Completely Standardized Expected Change for THETA-EPS

	Aquif	Geo	Precip	Hydro	Wet	Flood
Aquif	- -					
Geo	-0.099	- -				
Precip	0.034	0.204	- -			
Hydro	-0.017	0.002	-0.013	- -		
Wet	-0.019	-0.037	0.011	-0.190	- -	
Flood	-0.042	0.141	0.000	0.215	0.016	- -
Slope30	-0.035	-0.167	-0.039	0.024	0.194	-0.062
Farm	-0.047	0.015	-0.035	-0.005	0.188	0.052
Vege	-0.026	-0.037	0.141	-0.027	-0.486	0.166

Completely Standardized Expected Change for THETA-EPS

	Slope30	Farm	Vege
Slope30	- -		
Farm	0.172	- -	
Vege	0.055	-0.195	- -

Maximum Modification Index is 1171.62 for Element (15,11) of THETA-EPS

Standardized Solution

LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	0.636	- -	- -	- -	- -
est	0.562	- -	- -	- -	- -
pop	0.778	- -	- -	- -	- -
Noise	- -	0.981	- -	- -	- -
lu	- -	0.702	- -	- -	- -
Road	- -	0.267	- -	- -	- -
Aquif	- -	- -	0.351	- -	- -
Geo	- -	- -	0.475	- -	- -
Precip	- -	- -	1.209	- -	- -
Hydro	- -	- -	- -	0.182	- -
Wet	- -	- -	- -	0.547	- -
Flood	- -	- -	- -	0.529	- -
Slope30	- -	- -	- -	- -	0.374
Farm	- -	- -	- -	- -	0.581
Vege	- -	- -	- -	- -	0.983

Correlation Matrix of ETA

	LatentA	LatentB	LatentC	LatentD	LatentE
LatentA	1.000				
LatentB	0.869	1.000			
LatentC	0.356	0.352	1.000		
LatentD	-0.061	-0.157	0.139	1.000	
LatentE	-0.800	-0.969	-0.562	-0.706	1.000

PSI

	LatentA	LatentB	LatentC	LatentD	LatentE
LatentA	1.000				
LatentB	0.869	1.000			
LatentC	0.356	0.352	1.000		
LatentD	-0.061	-0.157	0.139	1.000	
LatentE	-0.800	-0.969	-0.562	-0.706	1.000

Completely Standardized Solution

LAMBDA-Y

	LatentA	LatentB	LatentC	LatentD	LatentE
occ	0.448	- -	- -	- -	- -
est	0.834	- -	- -	- -	- -
pop	0.925	- -	- -	- -	- -
Noise	- -	0.673	- -	- -	- -
lu	- -	0.832	- -	- -	- -
Road	- -	0.418	- -	- -	- -
Aquif	- -	- -	0.383	- -	- -
Geo	- -	- -	0.384	- -	- -
Precip	- -	- -	1.040	- -	- -
Hydro	- -	- -	- -	0.313	- -
Wet	- -	- -	- -	0.653	- -
Flood	- -	- -	- -	0.446	- -
Slope30	- -	- -	- -	- -	0.246

Farm	- -	- -	- -	- -	0.405
Vege	- -	- -	- -	- -	0.642

Correlation Matrix of ETA

	LatentA	LatentB	LatentC	LatentD	LatentE
LatentA	1.000				
LatentB	0.869	1.000			
LatentC	0.356	0.352	1.000		
LatentD	-0.061	-0.157	0.139	1.000	
LatentE	-0.800	-0.969	-0.562	-0.706	1.000

PSI

	LatentA	LatentB	LatentC	LatentD	LatentE
LatentA	1.000				
LatentB	0.869	1.000			
LatentC	0.356	0.352	1.000		
LatentD	-0.061	-0.157	0.139	1.000	
LatentE	-0.800	-0.969	-0.562	-0.706	1.000

THETA-EPS

occ	est	pop	Noise	lu	Road
0.800	0.305	0.145	0.547	0.307	0.825

THETA-EPS

Aquif	Geo	Precip	Hydro	Wet	Flood
0.853	0.853	-0.081	0.902	0.573	0.801

THETA-EPS

Slope30	Farm	Vege
0.940	0.836	0.588

Time used: 0.031 Seconds